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Numata

(10) **Patent No.: US 9,445,019 B2**
(45) **Date of Patent: Sep. 13, 2016**

(54) **SOLID-STATE IMAGE SENSOR AND IMAGE PICKUP APPARATUS INCLUDING THE SAME**

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(72) Inventor: **Aihiko Numata**, Inagi (JP)

(73) Assignee: **Canon Kabushiki Kaisha**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/016,146**

(22) Filed: **Feb. 4, 2016**

(65) **Prior Publication Data**

US 2016/0234446 A1 Aug. 11, 2016

(30) **Foreign Application Priority Data**

Feb. 10, 2015 (JP) 2015-024485

(51) **Int. Cl.**

H04N 3/14	(2006.01)
H04N 5/335	(2011.01)
H04N 5/359	(2011.01)
H04N 5/355	(2011.01)
H04N 5/378	(2011.01)

(52) **U.S. Cl.**

CPC ***H04N 5/359*** (2013.01); ***H04N 5/3559*** (2013.01); ***H04N 5/378*** (2013.01)

(58) **Field of Classification Search**

CPC H04N 5/359; H04N 5/3559; H04N 5/378; H04N 5/3696; H04N 5/23212; G02B 7/28; G02B 7/34

USPC 348/294, 298, 300, 302, 308, 312, 335, 348/340, 345, 348, 350, 352

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,866,947	B2 *	10/2014	Lenchenkov	H01L 27/14603 348/294
2003/0002836	A1 *	1/2003	Zhong	G02B 6/105 385/132
2011/0032398	A1 *	2/2011	Lenchenkov	H01L 27/14621 348/294
2012/0199893	A1	8/2012	Okabe et al.	
2013/0088626	A1	4/2013	Shoyama	
2014/0152878	A1 *	6/2014	Ozawa	H01L 27/14621 348/273
2015/0015752	A1	1/2015	Numata	

FOREIGN PATENT DOCUMENTS

JP	2004-120391 A	4/2004
JP	2004-363193 A	12/2004

* cited by examiner

Primary Examiner — Yogesh Aggarwal

(74) *Attorney, Agent, or Firm* — Canon USA, Inc. I.P. Division

(57) **ABSTRACT**

A solid-state image sensor includes pixels each including first and second photoelectric conversion portions provided in a substrate, the second photoelectric conversion portion having lower sensitivity than the first photoelectric conversion portion; a barrier region provided between the first and second photoelectric conversion portions; a waveguide provided on a light-entrance side of the substrate and including a core and a cladding; and a protective layer provided between the waveguide and the substrate. Seen in a direction perpendicular to the substrate, a center of an exit face of the core is on a first-photoelectric-conversion-portion side with respect to a center of the barrier region in each pixel in a central part of a pixel area. A standard deviation of a refractive-index distribution of the protective layer in a region directly below the exit face of the core is 0.1 or smaller in an in-plane direction of the substrate.

15 Claims, 19 Drawing Sheets

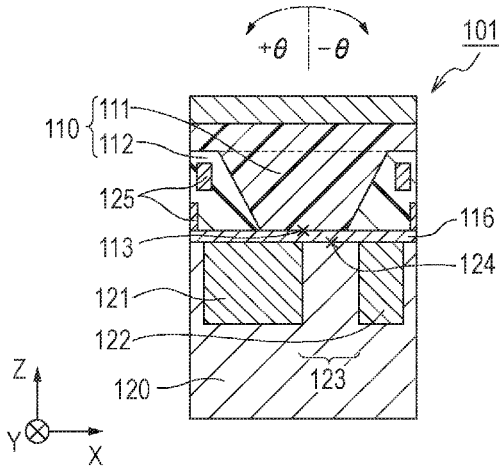


FIG. 1

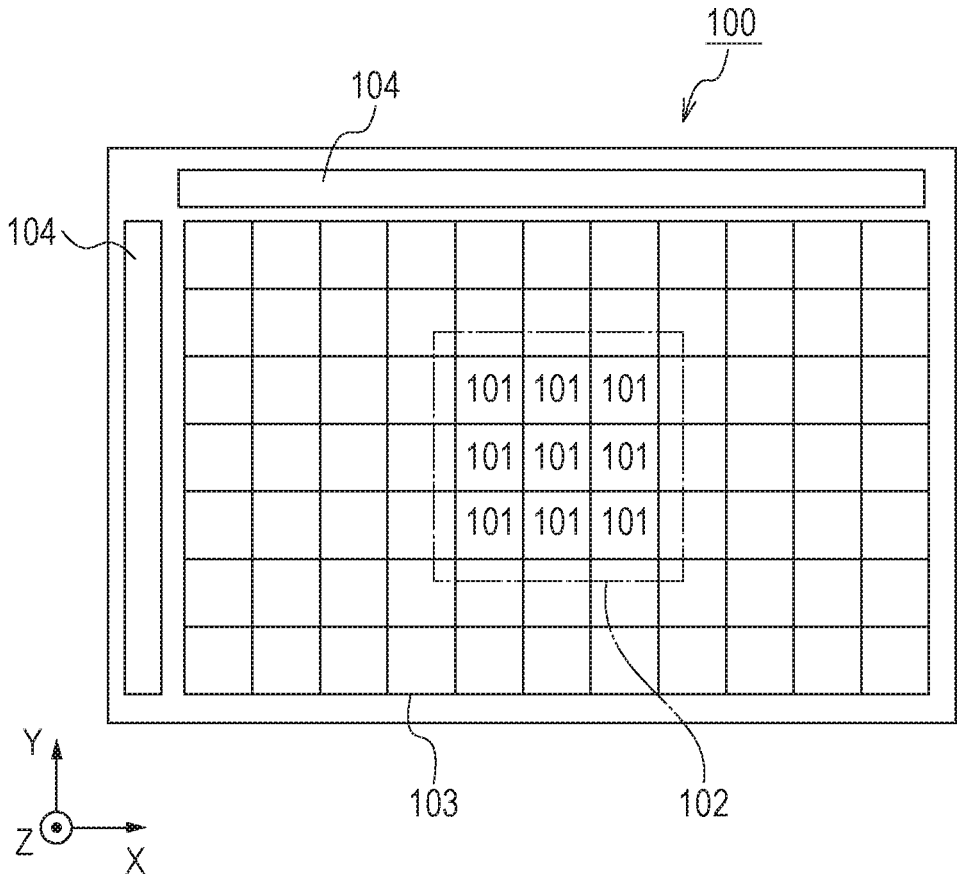


FIG. 2A

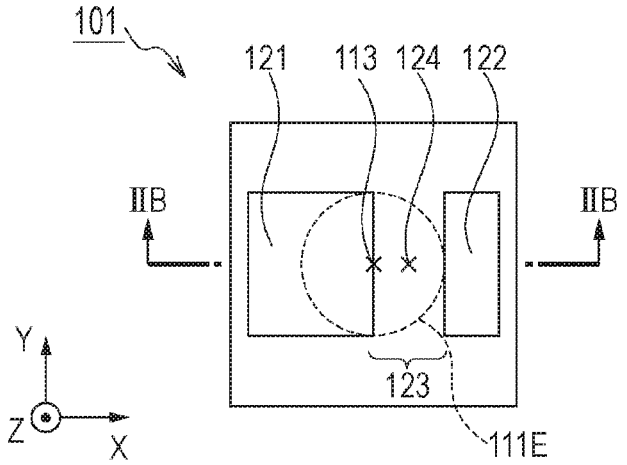


FIG. 2B

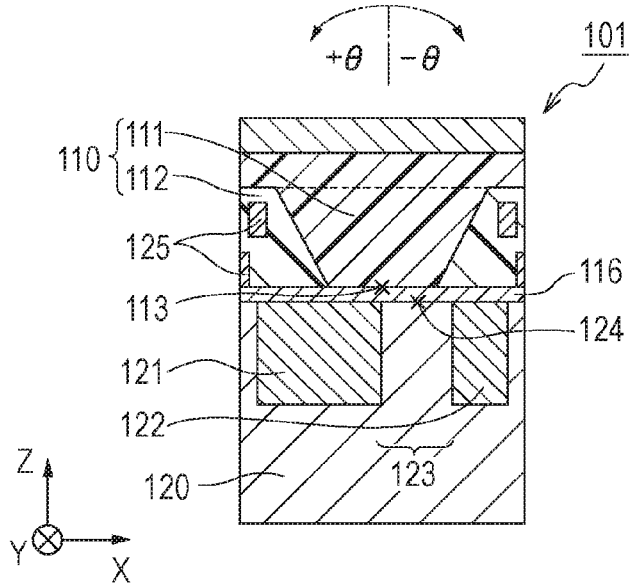


FIG. 2C

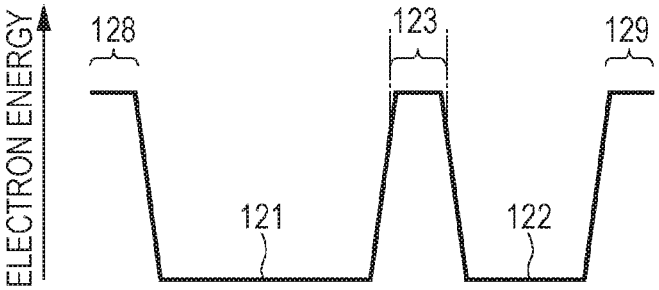
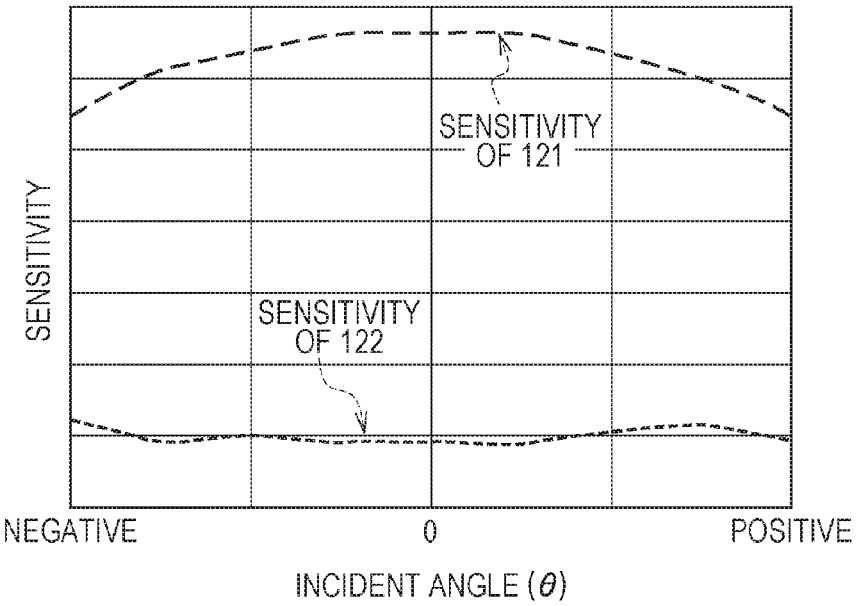


FIG. 3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SENSITIVITY OF 122
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INCIDENT ANGLE (θ)

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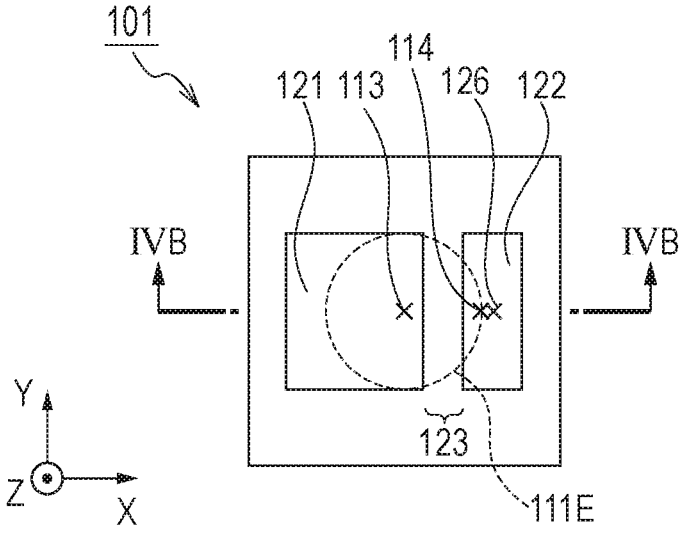
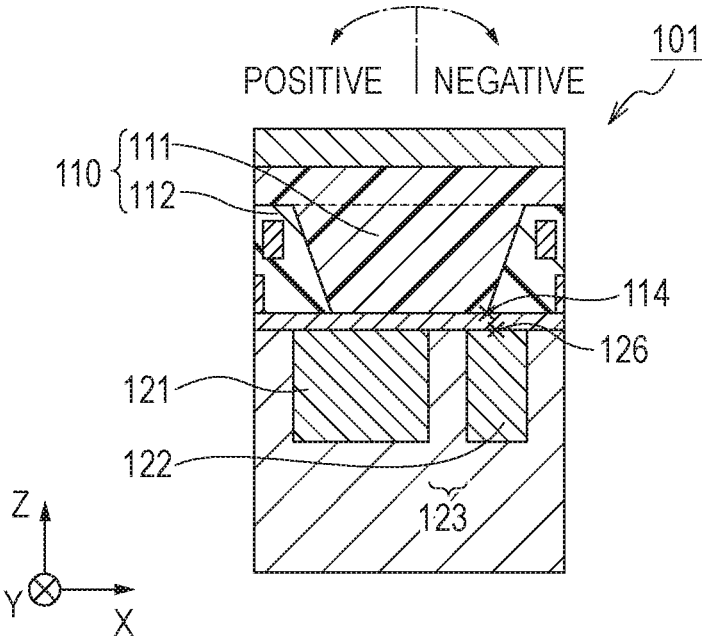

101
114
121
113
126
122
IVB
IVB
Y
Z
X
123
111E

FIG. 4B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NEGATIVE
101
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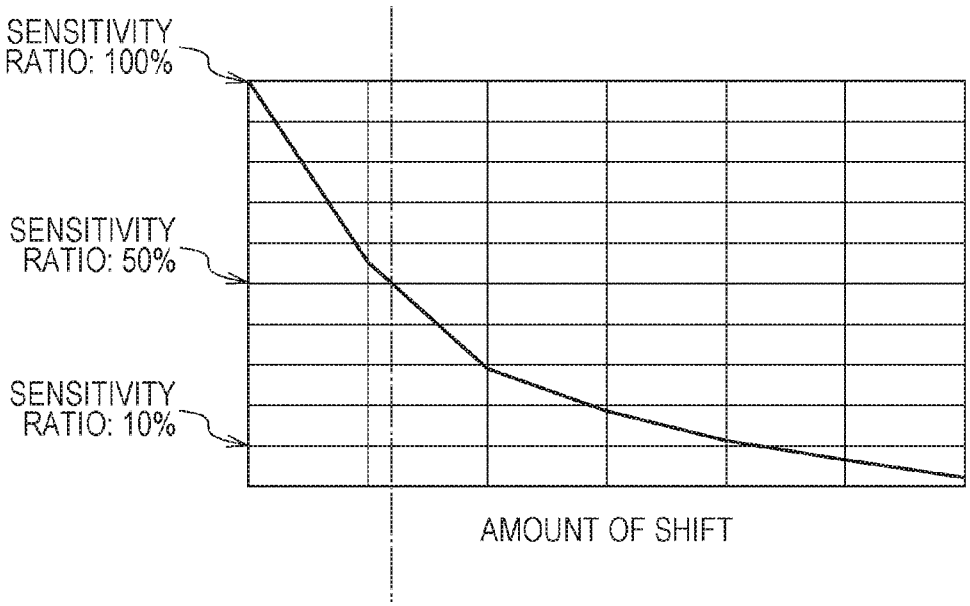
112
114
126
121
122
123
Z
Y
X

FIG. 5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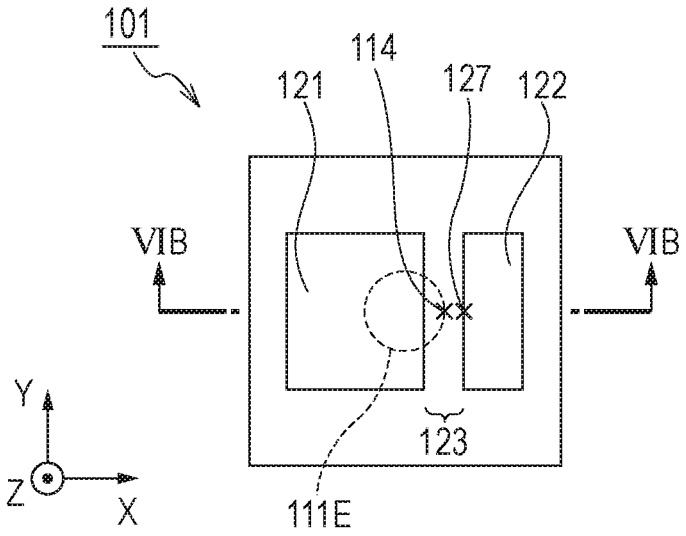
SENSITIVITY RATIO: 50%
SENSITIVITY RATIO: 10%
AMOUNT OF SHIFT

FIG. 6A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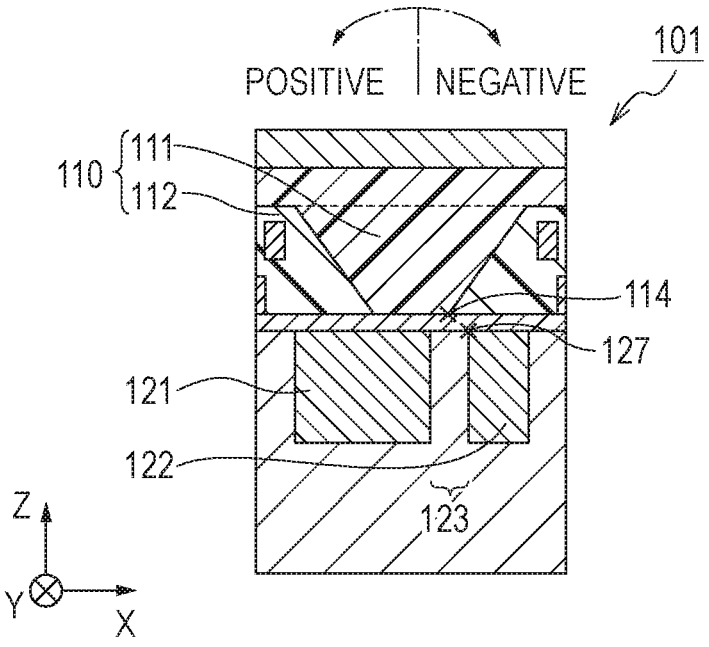
127
122
VIB
VIB
123
111E
Y
Z
X

FIG. 6B


POSITIVE
NEGATIVE
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110
111
112
114
127
121
122
123
Z
Y
X

FIG. 7A

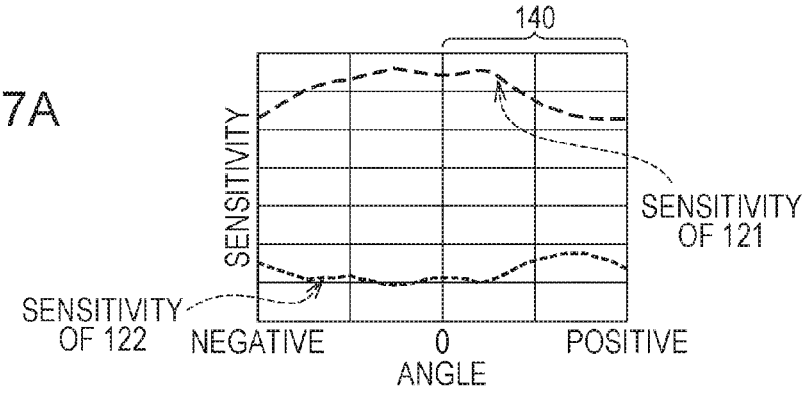


FIG. 7B

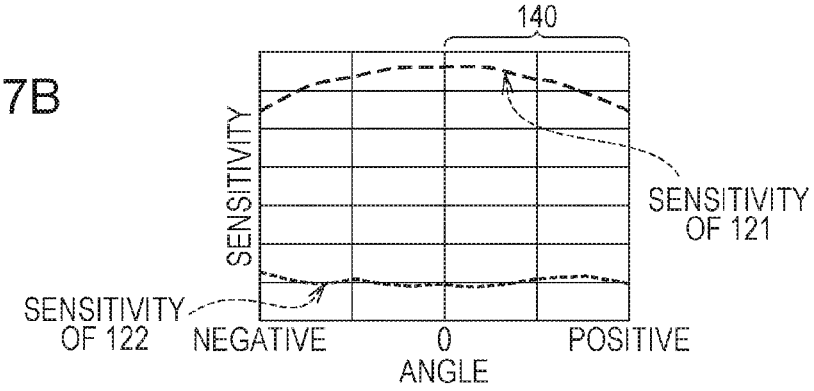


FIG. 7C

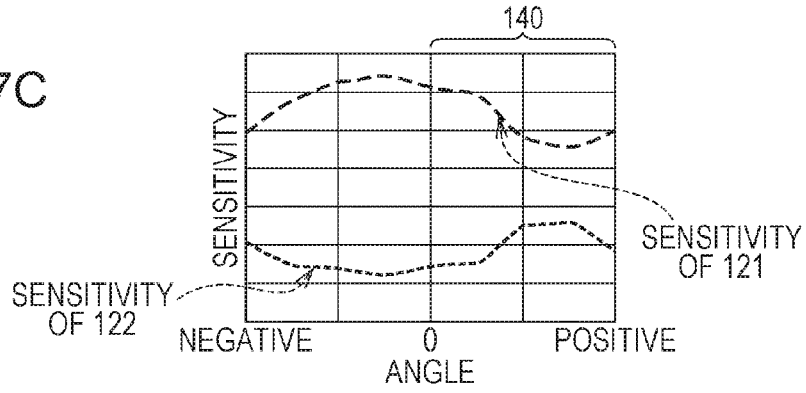


FIG. 7D

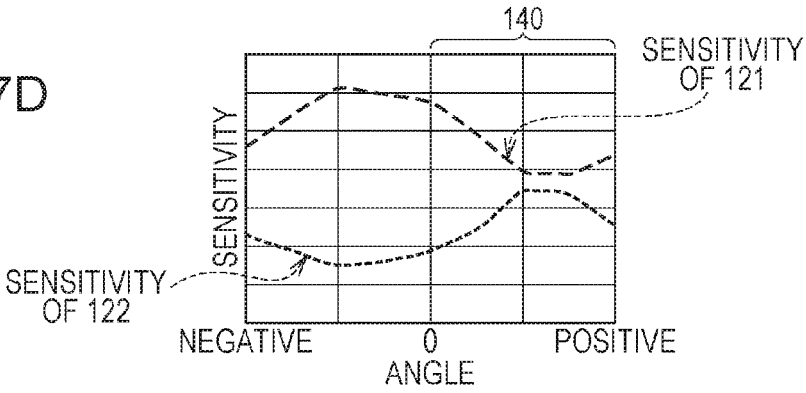


FIG. 8A

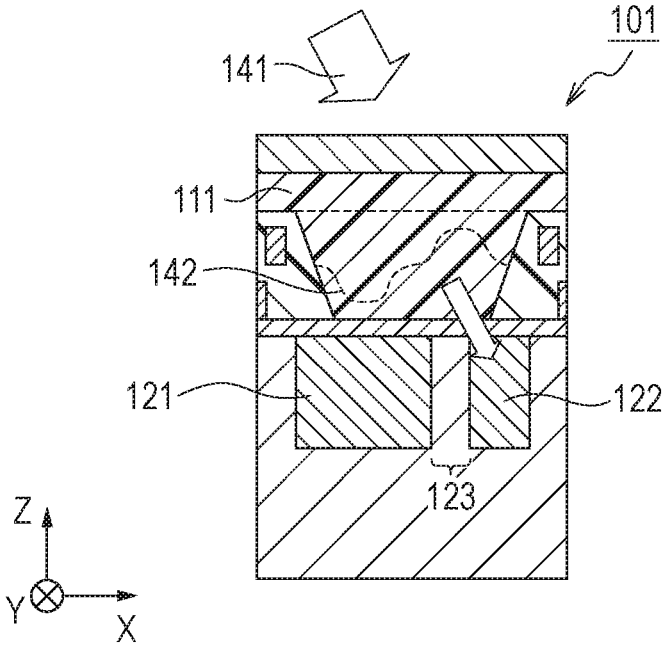


FIG. 8B

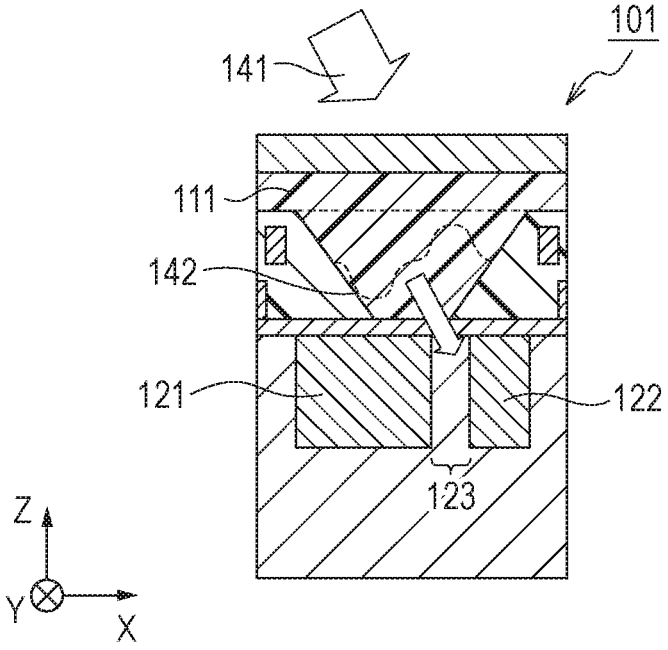


FIG. 9A

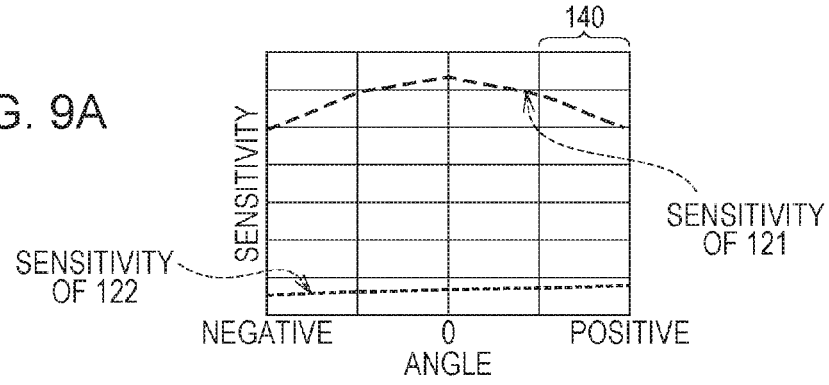


FIG. 9B

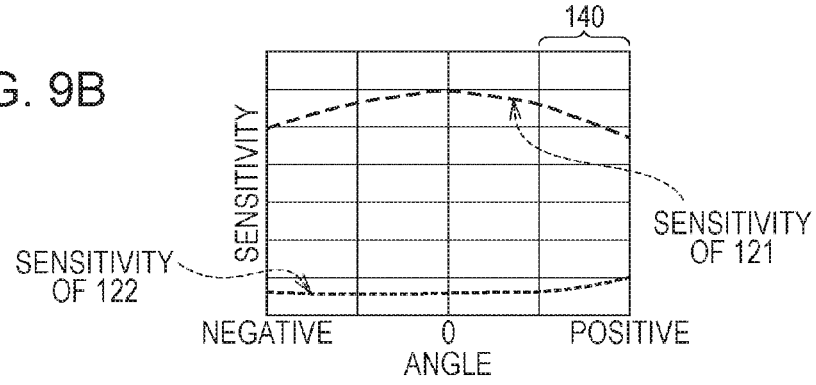


FIG. 9C

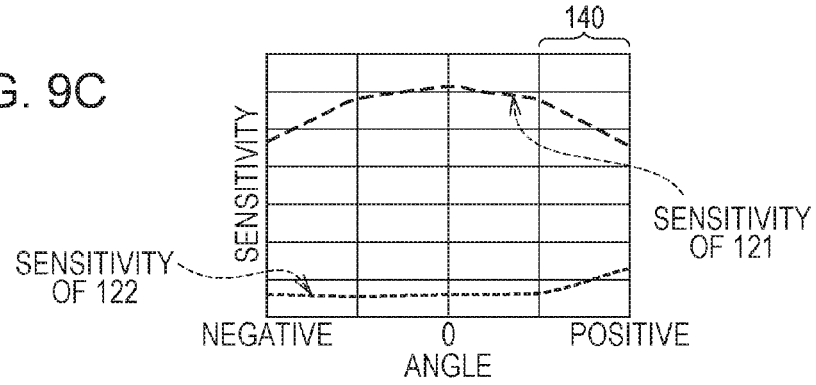


FIG. 9D

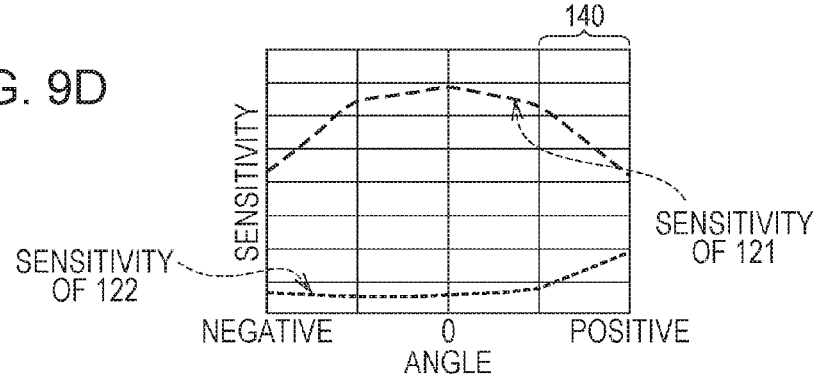


FIG. 10A

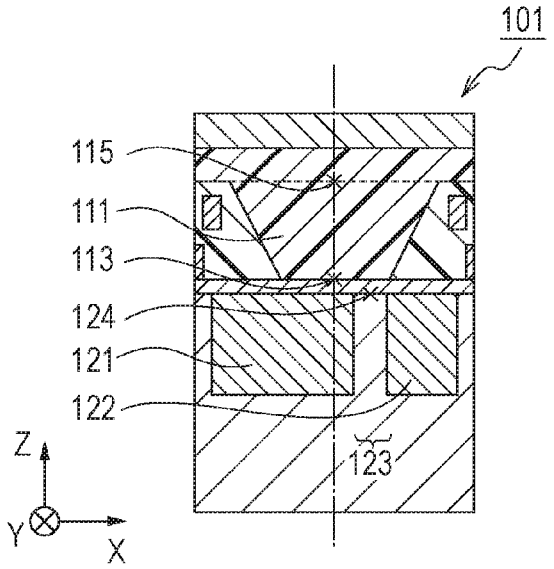


FIG. 10B

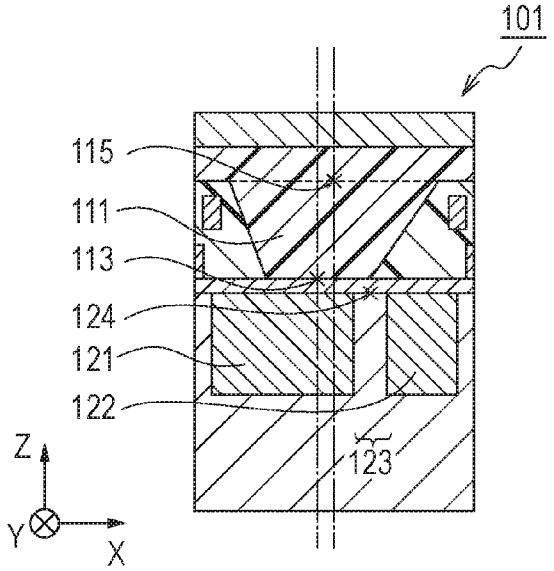


FIG. 10C

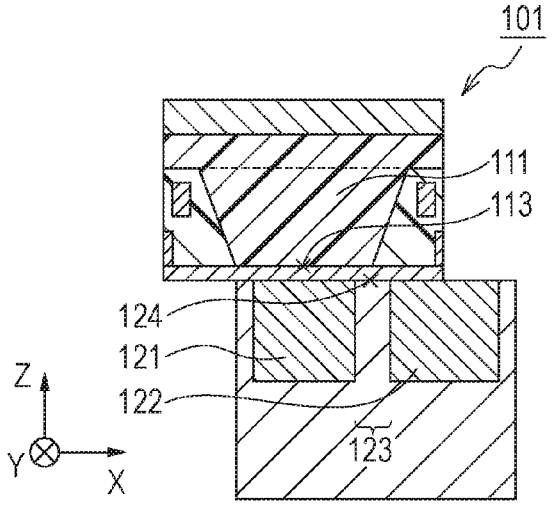


FIG. 11A

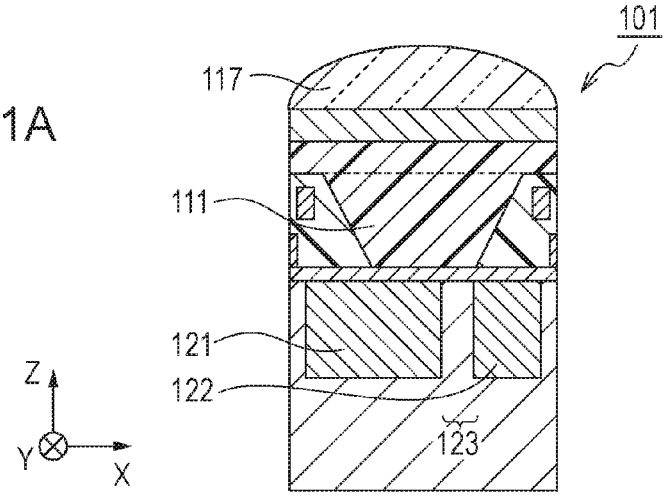


FIG. 11B

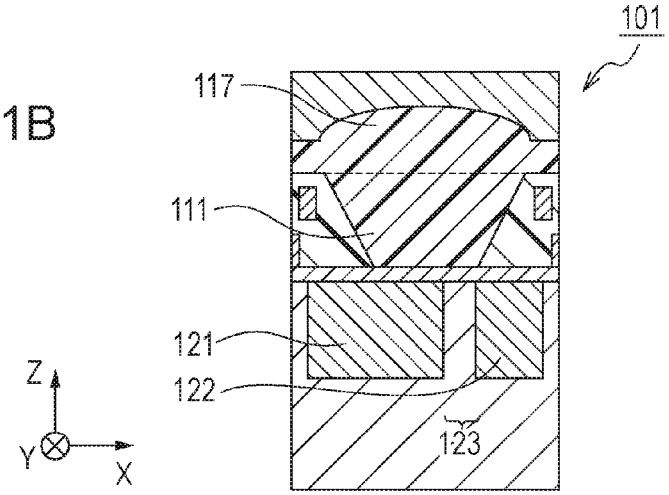


FIG. 11C

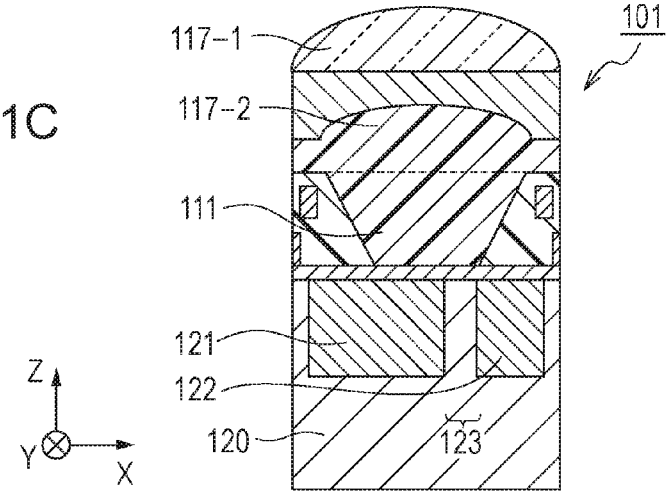


FIG. 12A

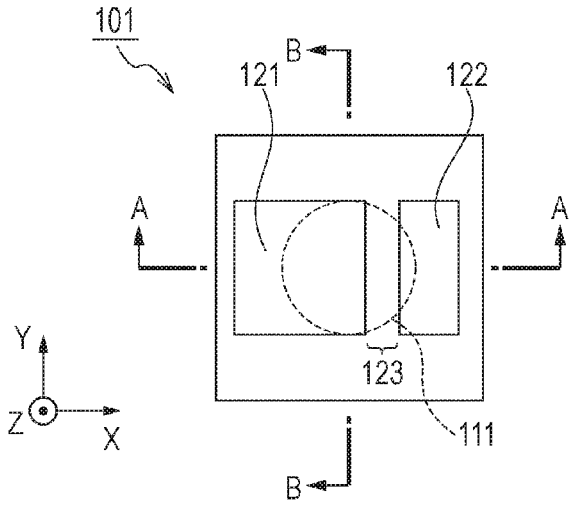


FIG. 12B

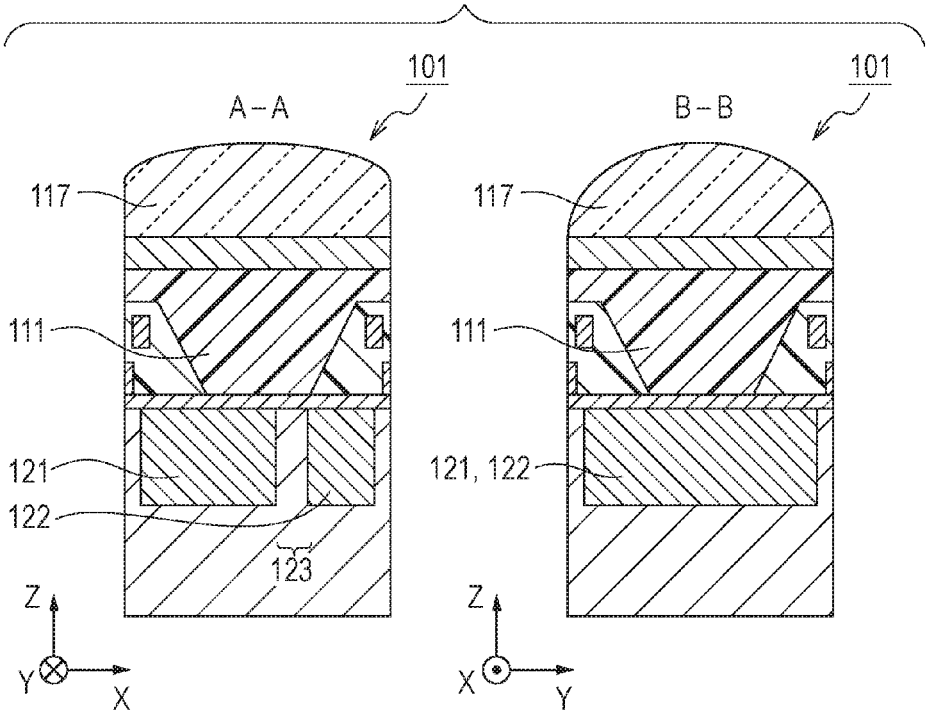


FIG. 12C

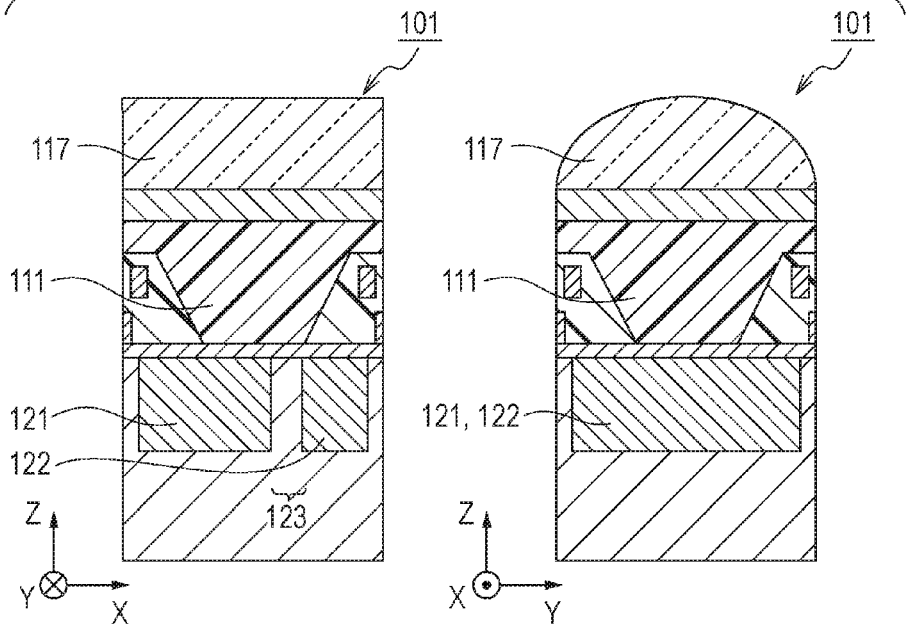


FIG. 12D

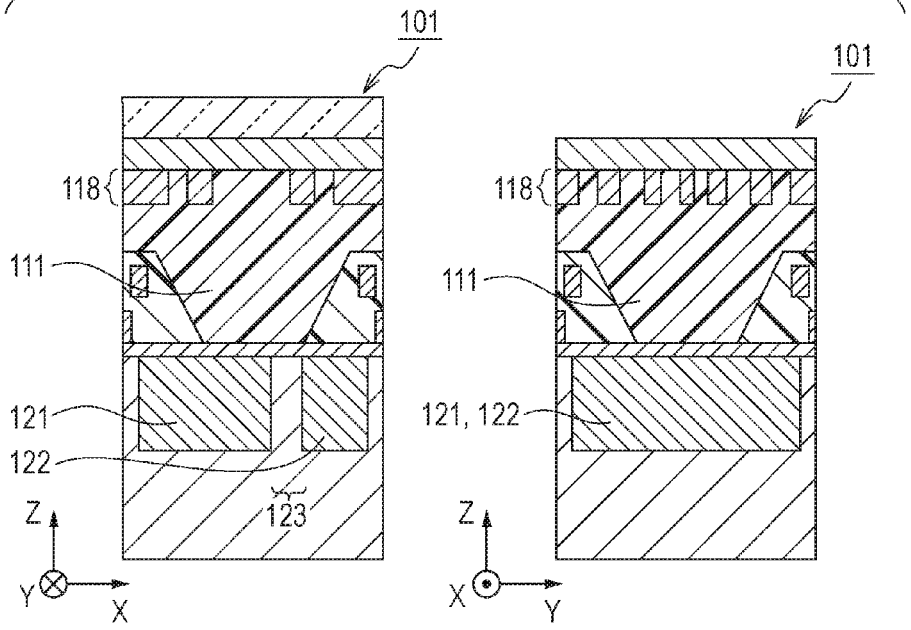


FIG. 13A

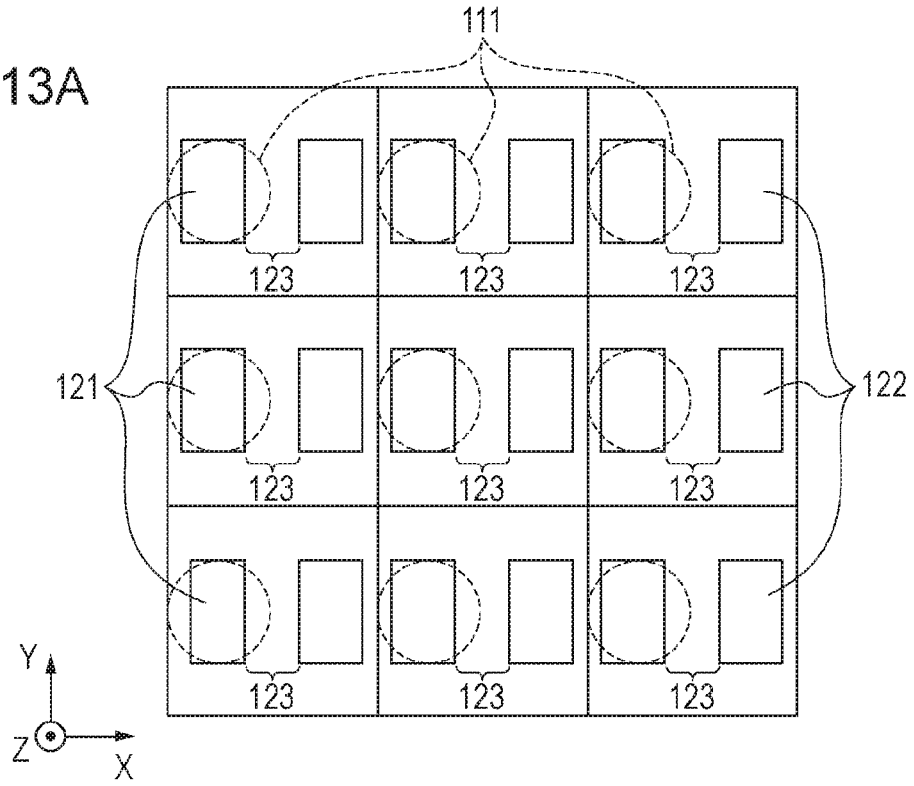


FIG. 13B

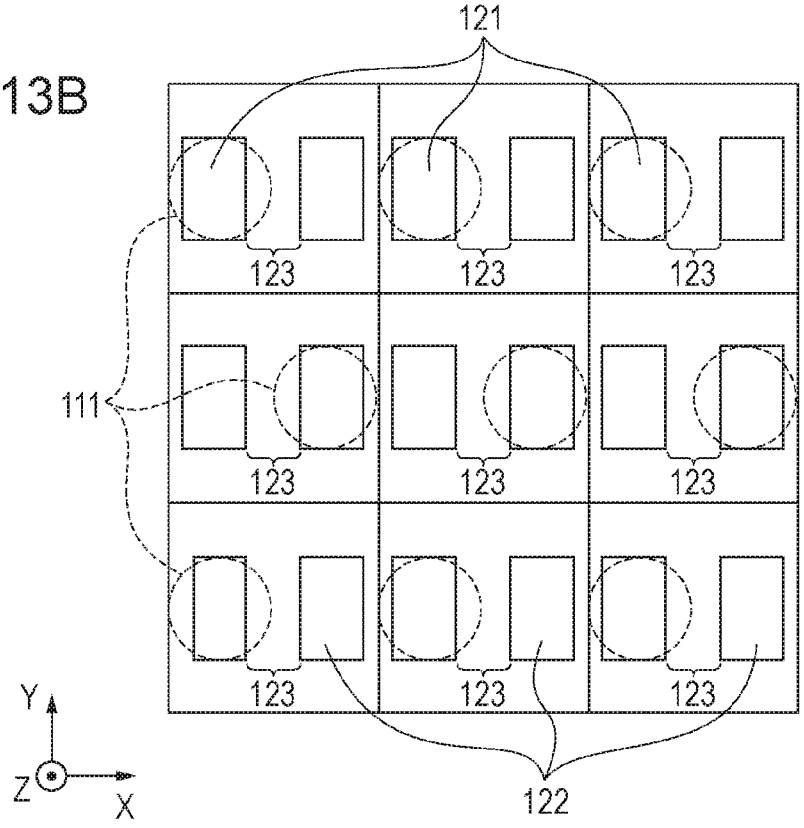


FIG. 14A

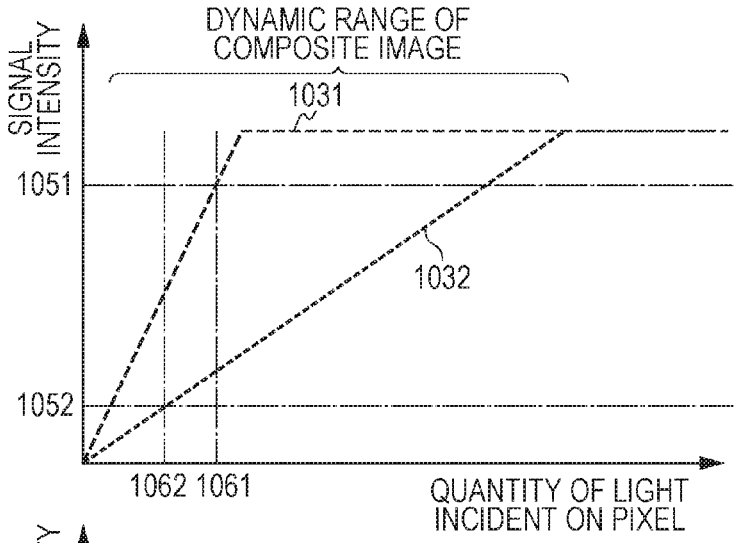


FIG. 14B

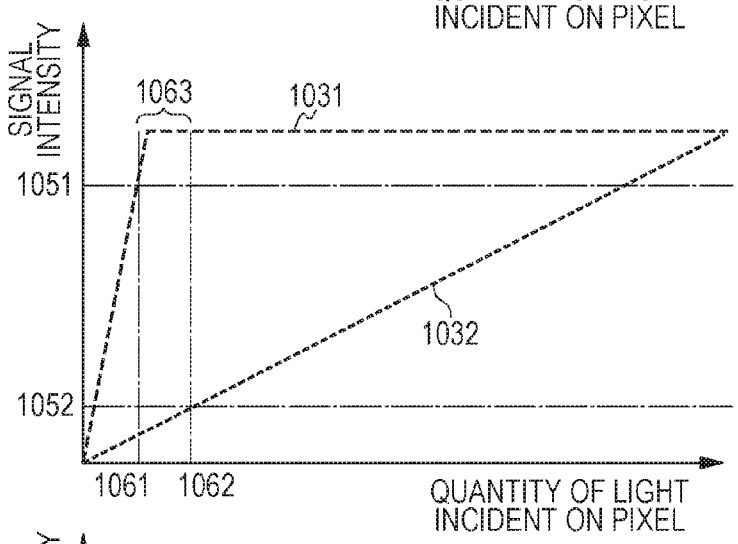


FIG. 14C

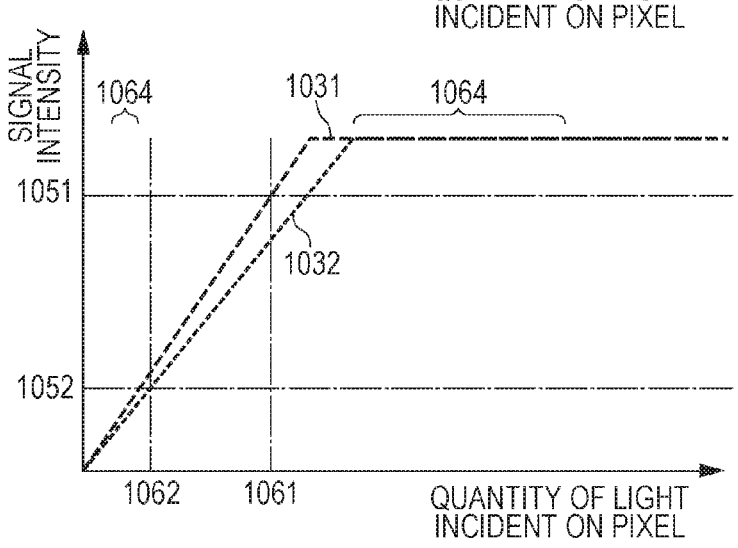


FIG. 15A

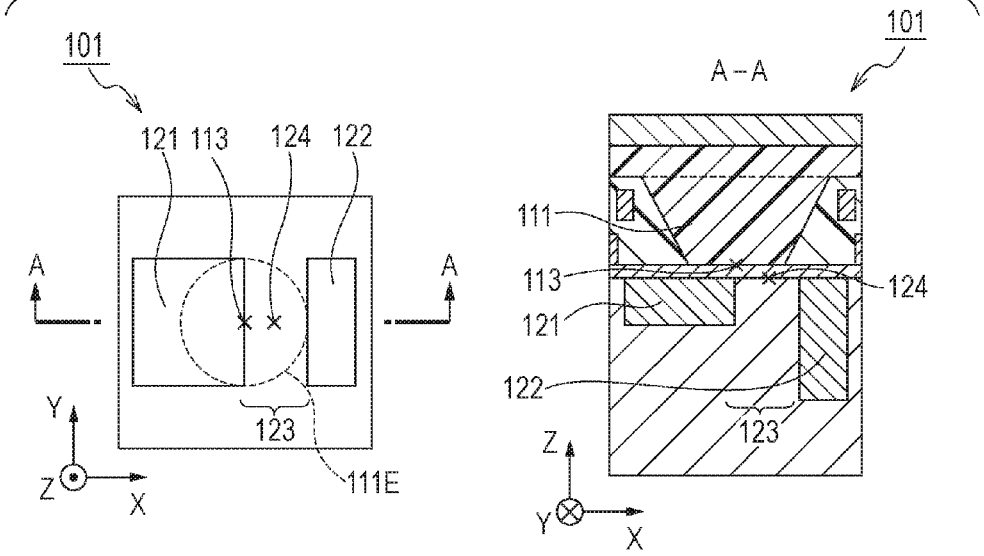


FIG. 15B

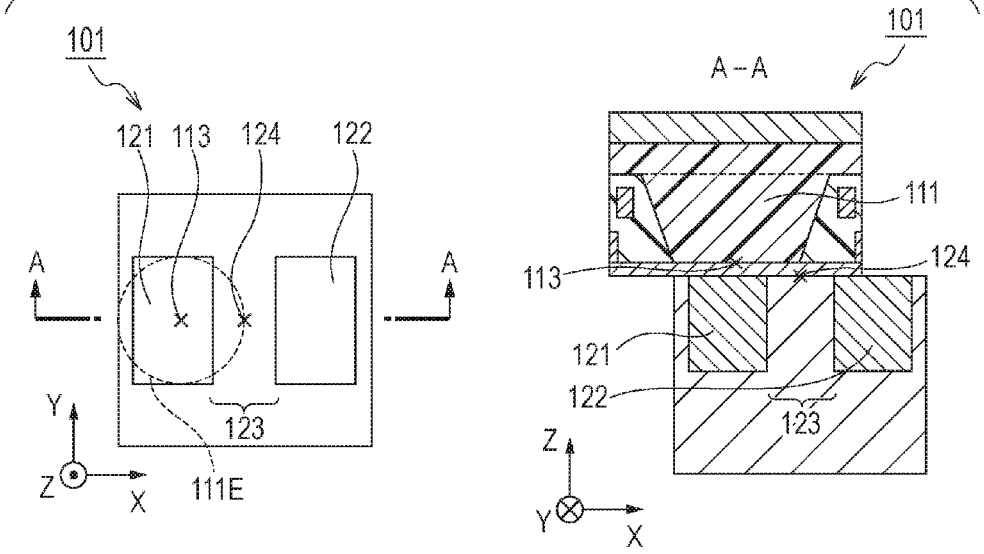


FIG. 16

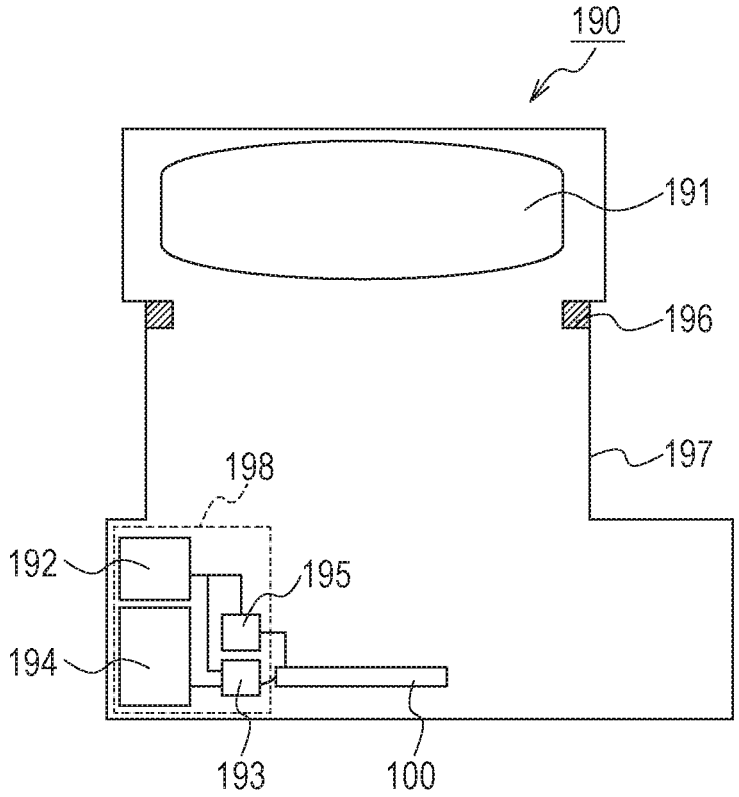


FIG. 17A

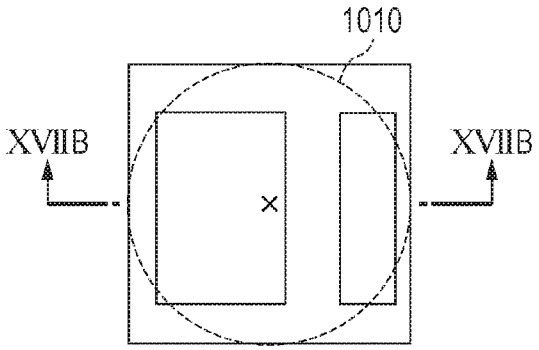


FIG. 17B

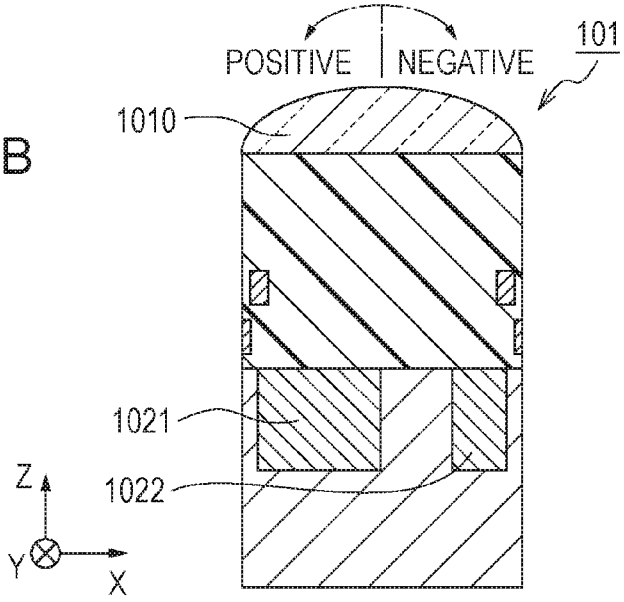


FIG. 17C

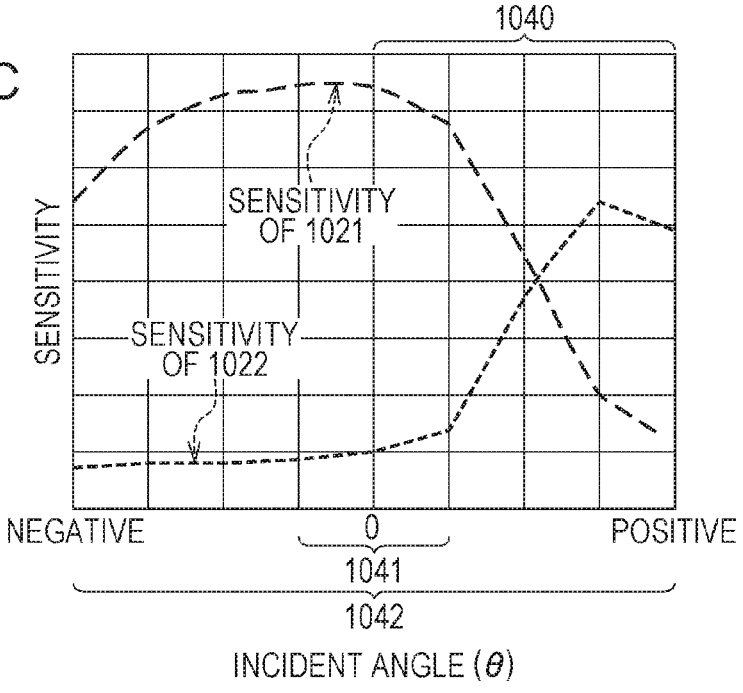


FIG. 18A

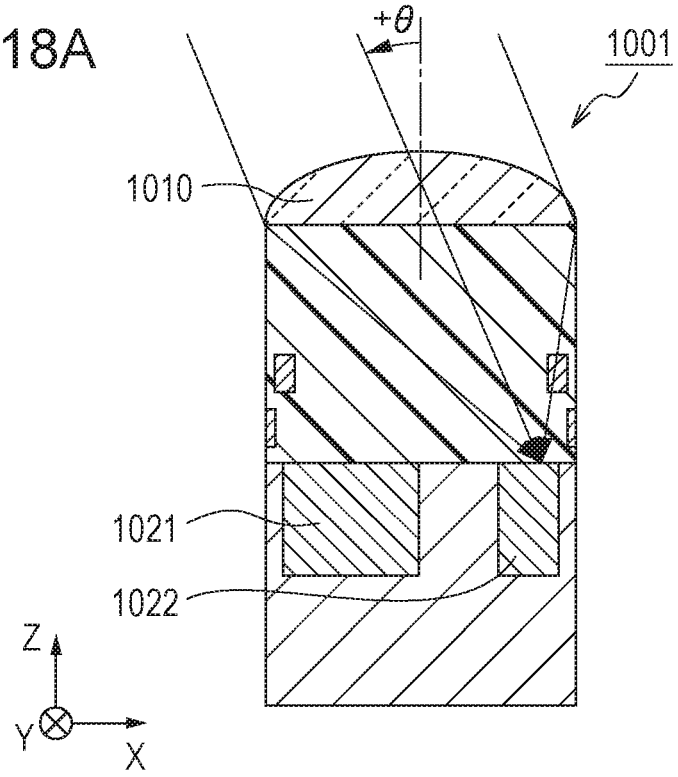
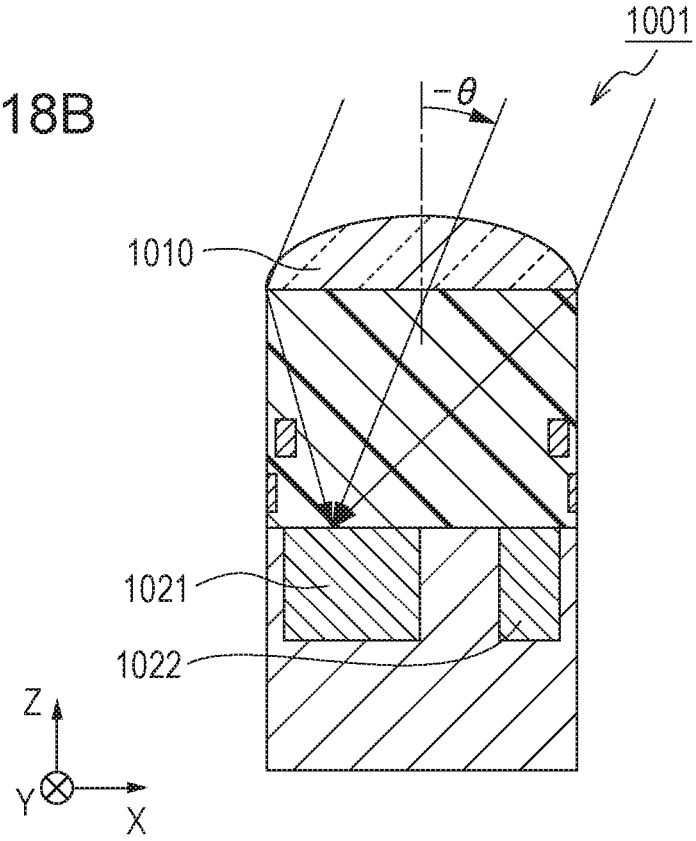


FIG. 18B



SOLID-STATE IMAGE SENSOR AND IMAGE PICKUP APPARATUS INCLUDING THE SAME

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to solid-state image sensors and particularly to a solid-state image sensor included in an image pickup apparatus such as a digital camera.

2. Description of the Related Art

In recent years, there has been an increasing demand for images taken by apparatuses, such as a digital camera, with wider dynamic ranges. In response to such a demand, a solid-state image sensor is proposed by Japanese Patent Laid-Open No. 2004-363193, in which a plurality of photoelectric conversion portions having different areas are provided in each pixel, so that two kinds of pixel signals, which are a high-sensitivity signal and a low-sensitivity signal, are acquired. With a combination of the two signals, the dynamic range is widened.

There has been another increasing demand for a camera capable of taking a moving image and a still image simultaneously. In general, to acquire a smooth moving image, the moving image may be taken with a period of exposure time that substantially corresponds to the frame rate of the reading by a solid-state image sensor. In contrast, to take a still image, the period of exposure time may be set in accordance with the speed at which the object moves. Hence, to take a still image and a moving image simultaneously, two kinds of pixel signals based on different periods of exposure time need to be acquired.

In Japanese Patent Laid-Open No. 2004-120391, a solid-state image sensor is disclosed that includes a plurality of photoelectric conversion elements (equivalent to the photoelectric conversion portions according to Japanese Patent Laid-Open No. 2004-363193) provided in each pixel and being based on different periods of exposure time so that a moving-image signal and a still-image signal can be acquired simultaneously. Photoelectric conversion elements for a relatively short period of exposure time each have a relatively large area, whereas photoelectric conversion elements for a relatively long period of exposure time each have a relatively small area. Furthermore, the sensitivity of photoelectric conversion elements for a moving image is different from the sensitivity of photoelectric conversion elements for a still image.

Note that "sensitivity of a photoelectric conversion portion" is defined by the ratio of the amount of charge accumulated in the photoelectric conversion portion to the quantity of light that is incident on the pixel per unit time.

In each of the solid-state image sensors disclosed by Japanese Patent Laid-Open No. 2004-363193 and Japanese Patent Laid-Open No. 2004-120391, a desired image is taken with a plurality of photoelectric conversion portions that are provided in each of pixels and having different levels of sensitivity. In each of the devices, light is condensed by a microlens provided on the surface of the pixel, whereby the light is guided to each of the photoelectric conversion portions. Hence, the quantity of light that is incident on each of the photoelectric conversion portions varies with the angle of incidence of the light on the pixel. Therefore, the photoelectric conversion portions each receive only a portion of the light that is emitted from a specific part of the exit pupil of an image pickup lens used. Consequently, a blurred image of an object that is out of focus may be distorted, resulting in a deterioration of image quality.

The present invention is to suppress the deterioration of image quality by reducing the angular dependence of the sensitivity of each of a plurality of photoelectric conversion portions provided in each pixel and having different levels of sensitivity.

SUMMARY OF THE INVENTION

A solid-state image sensor according to a first aspect of the present invention includes pixels provided in a pixel area. The pixels each include a first photoelectric conversion portion and a second photoelectric conversion portion that are provided in a substrate, the second photoelectric conversion portion having lower sensitivity than the first photoelectric conversion portion; a barrier region provided between the first photoelectric conversion portion and the second photoelectric conversion portion; a waveguide provided on a light-entrance side of the substrate and including a core and a cladding; and a protective layer provided between the waveguide and the substrate. When a surface of the substrate is seen in a direction perpendicular to the substrate, a center of an exit face of the core is positioned on a first-photoelectric-conversion-portion side with respect to a center of the barrier region at the surface of the substrate in each of pixels that are provided in a central part of the pixel area. A standard deviation of a distribution of refractive index of the protective layer in a region directly below the exit face of the core is 0.1 or smaller in an in-plane direction of the substrate.

An image pickup apparatus according to a second aspect of the present invention includes the solid-state image sensor according to the first aspect that is provided in a housing.

Further features of the present invention will become apparent from the following description of exemplary embodiments with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram illustrating an exemplary solid-state image sensor according to an embodiment of the present invention.

FIGS. **2**A to **2**C are diagrams illustrating an exemplary configuration of a pixel included in the solid-state image sensor.

FIG. **3** is a graph illustrating the angular dependence of the sensitivity of each of first and second photoelectric conversion portions.

FIG. **4**A is an exemplary plan view (XY-plane diagram) of the pixel seen from a light-entrance side.

FIG. **4**B is an exemplary sectional view of the pixel that is taken along line IVB-IVB illustrated in FIG. **4**A.

FIG. **5** is a graph illustrating a relationship between the amount of shift of a waveguide and the sensitivity ratio between the photoelectric conversion portions.

FIG. **6**A is an exemplary plan view (XY-plane diagram) of another pixel seen from the light-entrance side.

FIG. **6**B is an exemplary sectional view of the pixel that is taken along line VIB-VIB illustrated in FIG. **6**A.

FIGS. **7**A to **7**D are graphs illustrating the angular dependence of the sensitivity of each of the first and second photoelectric conversion portions with different amounts of shift of the waveguide.

FIG. **8**A is a diagram schematically illustrating how a ray of light at an incident angle $+\theta$ is propagated in a case where a second-photoelectric-conversion-portion-side end of an exit face of a core is positioned on a second-photoelectric-

conversion-portion side with respect to a boundary between a barrier region and the second photoelectric conversion portion.

FIG. **8**B is a diagram schematically illustrating how the ray of light at the incident angle +θ is propagated in a case where the second-photoelectric-conversion-portion-side end of the exit face of the core is positioned on a first-photoelectric-conversion-portion side with respect to the boundary between the barrier region and the second photoelectric conversion portion.

FIGS. **9**A to **9**D are graphs illustrating the angular dependence of the sensitivity of each of the first and second photoelectric conversion portions with different values of the optical distance between the exit face of the core and the surface of a substrate.

FIG. **10**A is a diagram illustrating an exemplary case where, seen in a direction perpendicular to the surface of the substrate, the center of an entrance face of the core coincides with the center of the exit face of the core.

FIG. **10**B is a diagram illustrating an exemplary case where the center of the entrance face of the core is shifted toward the second-photoelectric-conversion-portion side with respect to the center of the exit face of the core in an in-plane direction of the substrate.

FIG. **10**C is a diagram illustrating an exemplary case where a part of the core of the waveguide extends over an adjacent pixel.

FIG. **11**A is a diagram illustrating an exemplary case where a microlens is provided at the extreme end on the light-entrance side of the pixel.

FIG. **11**B is a diagram illustrating an exemplary case where a microlens is provided between the waveguide and the uppermost surface of the pixel.

FIG. **11**C is a diagram illustrating an exemplary case where microlenses are provided at the extreme end on the light-entrance side of the pixel and between the waveguide and the uppermost surface of the pixel, respectively.

FIGS. **12**A to **12**D are diagrams illustrating microlenses of different shapes that are applicable to the present invention.

FIGS. **13**A and **13**B are diagrams each illustrating the arrangement of the first photoelectric conversion portions and the second photoelectric conversion portions included in a plurality of pixels.

FIGS. **14**A to **14**C are graphs illustrating the dependence of the intensity of each of a high-sensitivity signal acquired by the first photoelectric conversion portion and a low-sensitivity signal acquired by the second photoelectric conversion portion upon the quantity of light that is incident on the pixel per unit time.

FIG. **15**A is a diagram illustrating an exemplary case where the first photoelectric conversion portion and the second photoelectric conversion portion have the same capacity but different Z-direction depths.

FIG. **15**B is a diagram illustrating an exemplary case where the first photoelectric conversion portion and the second photoelectric conversion portion have the same capacity and the same Z-direction depth.

FIG. **16** is a schematic diagram illustrating an image pickup apparatus including the solid-state image sensor according to the embodiment of the present invention.

FIG. **17**A is a plan view of a pixel included in a related-art solid-state image sensor that is seen from a light-entrance side.

FIG. **17**B is a diagram illustrating a sectional configuration of the pixel that is taken along line XVIIB-XVIIB illustrated in FIG. **17**A.

FIG. **17**C is an exemplary graph illustrating the dependence, upon the incident angle, of the sensitivity of each of the first and second photoelectric conversion portions included in a pixel according to the related art.

FIG. **18**A is a diagram illustrating how a ray of light that is incident on the related-art pixel at an incident angle +θ is propagated.

FIG. **18**B is a diagram illustrating how a ray of light that is incident on the related-art pixel at an incident angle −θ is propagated.

DESCRIPTION OF THE EMBODIMENTS

Embodiments of the solid-state image sensor according to the present invention will now be described with reference to the drawings, wherein like elements or elements having equivalent functions are denoted by like reference numerals, and redundant description thereof is omitted.

FIG. **1** is a schematic diagram illustrating an exemplary solid-state image sensor **100** according to a general embodiment of the present invention. The solid-state image sensor **100** includes a pixel area **103** in which a plurality of pixels are provided, and an area in which peripheral circuits **104** are provided.

Pixels

Pixels **101** refer to pixels provided in a central part **102** of the pixel area **103**. Herein, the pixels **101** provided in the central part **102** refer to pixels whose centroids are positioned in the central part **102**.

The central part **102** refers to an area within a predetermined distance from the center of the pixel area **103**. The predetermined distance is preferably ¼ of the length of the diagonal of the pixel area **103** or shorter, or more preferably 1/20 of the length of the diagonal of the pixel area **103** or shorter.

In the solid-state image sensor **100** illustrated in FIG. **1**, the pixels **101** provided in the central part **102** are in a 3-by-3 arrangement, for example. The arrangement of the pixels **101** is not limited to such a pattern. At least one pixel **101** only needs to be provided in the central part **102**. Moreover, pixels having the same configuration as the pixel **101** may be provided outside the central part **102**.

FIGS. **2**A to **2**C are diagrams illustrating an exemplary configuration of the pixel **101** included in the solid-state image sensor **100**. FIG. **2**A illustrates a layout of the pixel **101** at a surface of a substrate **120** that is seen in a direction (Z direction) perpendicular to the substrate **120**. FIG. **2**B is an XZ sectional view of the pixel **101** that is taken along line IIB-IIB illustrated in FIG. **2**A.

The pixel **101** includes, in order from a light-entrance side thereof, a waveguide **110** including a core **111** and a cladding **112**, a protective layer **116**, and the substrate **120**. The substrate **120** includes a first photoelectric conversion portion **121**, a second photoelectric conversion portion **122**, and a barrier region **123** provided between the photoelectric conversion portions **121** and **122**.

Photoelectric Conversion Portions and Barrier Region

The photoelectric conversion portions **121** and **122** are formed by producing potential variations in the substrate **120** by ion implantation or the like. The substrate **120** is made of silicon or the like that absorbs light having a wavelength band to be detected. The barrier region **123** has a potential barrier that suppresses the occurrence of charge crosstalk between the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122**. As illustrated in FIG. **2**C, the barrier region **123** corresponds to a region between the first photoelectric conversion portion

121 and the second photoelectric conversion portion 122 where the potential of the potential barrier is 90% of the highest value or above, inclusive of the highest value.

The size of the potential barrier in the barrier region 123 may be determined with consideration for the permissible amount of charge crosstalk between the first photoelectric conversion portion 121 and the second photoelectric conversion portion 122. To acquire pixel signals for the respective photoelectric conversion portions 121 and 122 independently of each other, the potential barrier may be made high so that the amount of charge crosstalk is reduced. More specifically, the potential barrier in the barrier region 123 may have a height greater than or equal to the height of potential barriers (denoted by reference numerals 128 and 129 in FIG. 2C) provided in other regions excluding the barrier region 123 and surrounding the first photoelectric conversion portion 121 and the second photoelectric conversion portion 122. In such a configuration, the crosstalk between the first photoelectric conversion portion 121 and the second photoelectric conversion portion 122 can be reduced to approximately the same level as the crosstalk between pixels. However, if the permissible amount of charge crosstalk is large, the potential barrier in the barrier region 123 may be lower than the potential barriers provided in the other regions excluding the barrier region 123 and surrounding the first photoelectric conversion portion 121 and the second photoelectric conversion portion 122.

To produce potential variations in the pixel 101 as illustrated in FIG. 2C, a potential barrier may be formed by implanting ions into a region corresponding to the barrier region 123, not in regions corresponding to the first photoelectric conversion portion 121 and the second photoelectric conversion portion 122. Alternatively, ions may be implanted into both the photoelectric conversion portions 121 and 122 and the barrier region 123. In that case, ions implanted into the regions corresponding to the photoelectric conversion portions 121 and 122 and ions implanted into the barrier region 123 may have opposite conductivity characteristics.

The first photoelectric conversion portion 121 and the second photoelectric conversion portion 122 do not necessarily need to be arranged side by side in the X direction as illustrated in FIGS. 2A and 2B and may be arranged side by side in a direction that is at an angle larger than 0° with respect to the X axis. Moreover, the shape of the opening in the surface of the substrate 120 at each of the first photoelectric conversion portion 121 and the second photoelectric conversion portion 122 is not limited to a rectangle as illustrated in FIG. 2A and may be a circle, an ellipse, a polygon, or the like. The corners of the polygon may each be rounded in a manufacturing process.

Protective Layer

The protective layer 116 is provided for reducing the damage to the photoelectric conversion portions 121 and 122 during a manufacturing process and for preventing impurities from entering the photoelectric conversion portions 121 and 122 from other members such as wiring lines 125. In addition, the protective layer 116 may have another function such as an anti-reflection function of suppressing the reflection of light that is incident on the photoelectric conversion portions 121 and 122 from the core 111. Moreover, the protective layer 116 may include a plurality of layers that are stacked in the direction perpendicular to the surface of the substrate 120.

Waveguide

The waveguide 110 is formed of different materials that are combined such that the core 111 has a higher refractive index than the cladding 112. The materials for the core 111 and the cladding 112 can be selected from inorganic materials such as silicon oxide, silicon nitride, silicon oxynitride, silicon carbide, and borophosphosilicate glass (BPSG), and organic materials such as polymer and resin.

A broken line 111E illustrated in FIG. 2A defines an end facet of the core 111 that is on the side of the substrate 120, i.e., an exit face. In FIG. 2A, the waveguide 110 is provided such that a center 113 of the exit face 111E of the core 111 is positioned on the first-photoelectric-conversion-portion side (−X side) with respect to a center 124 of the barrier region 123. Herein, the center 124 of the barrier region 123 at the surface of the substrate 120 refers to the centroid of a plan-view shape, seen in the Z direction, of the barrier region 123 at the surface of the substrate 120. Likewise, the center 113 of the exit face 111E of the core 111 refers to the centroid of the plan-view shape, seen in the Z direction, of the exit face 111E of the core 111. Hereinafter, for simplicity, the amount of shift of the center 113 of the exit face 111E of the core 111 in the −X direction with respect to the center 124 of the barrier region 123 at the surface of the substrate 120 is occasionally referred to as the amount of shift of the waveguide 110.

Light that is propagated in the waveguide 110 concentrates on the core 111. Therefore, the quantity of light that is incident on the first photoelectric conversion portion 121 provided relatively near the center 113 of the exit face 111E of the core 111 is larger than the quantity of light that is incident on the second photoelectric conversion portion 122 provided relatively far from the center 113 of the exit face 111E of the core 111. That is, shifting the center 113 of the exit face 111E of the core 111 toward the first-photoelectric-conversion-portion side with respect to the center 124 of the barrier region 123 at the surface of the substrate 120 makes the sensitivity of the first photoelectric conversion portion 121 higher than the sensitivity of the second photoelectric conversion portion 122.

The cladding 112 is provided with wiring lines 125 that transmit driving signals for setting periods of exposure time of the respective photoelectric conversion portions 121 and 122 and read the signals acquired by the photoelectric conversion portions 121 and 122. The driving signals that are transmitted from the peripheral circuits 104 to the pixel 101 through the wiring lines 125 activate the first photoelectric conversion portion 121 and the second photoelectric conversion portion 122 on the basis of respective desired periods of exposure time.

SUMMARY

To summarize, in the pixel 101 included in the solid-state image sensor 100 according to the general embodiment of the present invention, light that is incident on the pixel 101 is guided to each of the photoelectric conversion portions 121 and 122 by the waveguide 110 provided in such a manner as to be shifted with respect to the center 124 of the barrier region 123 at the surface of the substrate 120. Employing such a configuration makes the angular dependence of the sensitivity of each of a plurality of photoelectric conversion portions 121 and 122, which have different levels of sensitivity, lower than that observed in the related-art solid-state image sensor in which light that is incident on the pixel is guided to each of the photoelectric conversion portions by using a microlens. Comparison with the case of the related-art solid-state image sensor will be given below.

Angular Dependence of Related-Art Solid-State Image Sensor

FIG. **17**A is a diagram illustrating a layout of a pixel **1001** included in the related-art solid-state image sensor, taken for comparison, at a surface (XY plane) of a substrate that is seen from a light-entrance side (seen in a direction perpendicular to the substrate). FIG. **17**B is a diagram illustrating a configuration of section (XZ-plane) of the pixel **1001** that is taken along line XVIIB-XVIIB illustrated in FIG. **17**A. The pixel **1001** illustrated in FIG. **17**B includes no waveguide including a core and a cladding. The pixel **1001** is different from the pixel **101** of the solid-state image sensor **100** according to the general embodiment of the present invention illustrated in FIGS. **2**A to **2**C in that light that is incident on the pixel **1001** is guided to each of first and second photoelectric conversion portions **1021** and **1022** by a microlens **1010**.

FIGS. **18**A and **18**B illustrate how a ray of light that is incident on the pixel **1001** of the related-art solid-state image sensor is propagated. FIG. **18**A illustrates how a ray of light traveling in the −Z direction and toward the +X side (at an incident angle +θ) is propagated. FIG. **18**B illustrates how a ray of light traveling in the −Z direction and toward the −X side (at an incident angle −θ) is propagated. As illustrated in FIGS. **18**A and **18**B, in accordance with the focusing characteristic of the microlens **1010**, the ray of light traveling in the −Z direction and toward the +X side is selectively guided to the second photoelectric conversion portion **1022**, whereas the ray of light traveling in the −Z direction and toward the −X side is selectively guided to the first photoelectric conversion portion **1021**. Consequently, the second photoelectric conversion portion **1022** is more sensitive to the ray of light traveling in the −Z direction and toward the +X side, whereas the first photoelectric conversion portion **1021** is more sensitive to the ray of light traveling in the −Z direction and toward the −X side. That is, the sensitivity of the photoelectric conversion portions **1021** and **1022** depends on the angle.

FIG. **17**C is an exemplary graph illustrating the dependence, on the incident angle, of the sensitivity of each of the photoelectric conversion portions **1021** and **1022** included in the pixel **1001** provided with the microlens **1010**. The horizontal axis represents the incident angle θ of a ray of light that is incident on the pixel **1001**. A case of θ=0° means that a ray of light parallel to the optical axis of the microlens **1010** is incident on the pixel **1001**.

As can be seen from FIG. **17**C, the angular dependence of the sensitivity is particularly high in an angle range **1040** for both the first photoelectric conversion portion **1021** and the second photoelectric conversion portion **1022**. If the angular dependence of the sensitivity of the photoelectric conversion portion is high, the photoelectric conversion portion receives only a ray of light emitted from a specific part of the exit pupil of the image pickup lens used. Consequently, a blurred image of an object that is out of focus may be distorted, resulting in a deterioration of image quality.

Position of Waveguide and Angular Dependence

Now, a case where the microlens as the cause for the angular dependence of the pixel is omitted will be discussed. The microlens provided on the light-emission side of the pixel condenses light incident on the pixel from the outside and guides the light to the first photoelectric conversion portion and to the second photoelectric conversion portion provided in the pixel. Hence, if the microlens is simply omitted, particularly, a ray of light that is obliquely incident on the pixel travels straightly, without being condensed, and a portion thereof enters an adjacent pixel. Such a situation increases so-called crosstalk between pixels. Consequently, image quality may be deteriorated.

In contrast, the pixel **101** of the solid-state image sensor **100** according to the general embodiment of the present invention includes the waveguide **110** whose center **113** of the exit face **111**E of the core **111** is shifted toward the first-photoelectric-conversion-portion side with respect to the center **124** of the barrier region **123** at the surface of the substrate **120**, whereby light is guided to the photoelectric conversion portions **121** and **122**, instead of condensing the light by using the microlens. The light that enters the waveguide **110** is emitted after being coupled with a plurality of waveguide modes. Therefore, the intensity distribution of the light at the exit face **111**E of the waveguide **110** is more even than that of the light condensed by the microlens. Consequently, the angular dependence of the sensitivity of each of the photoelectric conversion portions **121** and **122** is reduced. Furthermore, a ray of light that is obliquely incident on the pixel **101** is efficiently guided to the photoelectric conversion portions **121** and **122** by the waveguide **110**. Therefore, the crosstalk between pixels **101** is also reduced.

FIG. **3** is a graph illustrating the angular dependence of the sensitivity of each of the photoelectric conversion portions **121** and **122** included in the pixel **101** illustrated in FIGS. **2**A to **2**C. The horizontal axis represents the incident angle (θ), in the XZ plane, of a ray of light that is incident on the pixel **101**. This applies to all graphs illustrating the angular dependence of the sensitivity of each of the photoelectric conversion portions.

As is obvious from the comparison between FIG. **3** and FIG. **17**C, the dependence of the sensitivity of each of the photoelectric conversion portions **121** and **122** upon the incident angle is far lower than that of each of the photoelectric conversion portions **1021** and **1022**. The photoelectric conversion portions **121** and **122** each exhibit a substantially uniform sensitivity characteristic, regardless of incident angle. That is, the photoelectric conversion portions **121** and **122** can substantially evenly receive rays of light emitted from all over the exit pupil of the image pickup lens used. Consequently, the distortion of a blurred image of an object that is out of focus is reduced, and image quality is improved.

Amount of Shift of Waveguide from Viewpoint of Sensitivity Ratio

The amount of shift of the center **113** of the exit face **111**E of the core **111** with respect to the center **124** of the barrier region **123** may be changed in accordance with the required sensitivity ratio between the photoelectric conversion portions **121** and **122**. To make the sensitivity of the first photoelectric conversion portion **121** satisfactorily higher than the sensitivity of the second photoelectric conversion portion **122**, a second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** may be positioned on the first-photoelectric-conversion-portion side with respect to a center **126** of the second photoelectric conversion portion **122** as illustrated in FIGS. **4**A and **4**B. FIG. **4**A is a plan view (XY-plane diagram) of the pixel **101** seen from the light-entrance side (the pixel **101** seen in the direction perpendicular to the substrate **120**). FIG. **4**B is a sectional view of the pixel **101** that is taken along line IVB-IVB illustrated in FIG. **4**A. The second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** refers to a point of a plan-view shape, seen in the Z direction, of the exit face **111**E of the core **111** that is at the extreme end on the second-photoelectric-conversion-portion side (a point where the X coordinate is largest in

FIG. **4**A). The center **126** of the second photoelectric conversion portion **122** refers to the centroid of the plan-view shape, seen in the Z direction, of the second photoelectric conversion portion **122** at the surface of the substrate **120**.

FIG. **5** illustrates a relationship between the amount of shift of the waveguide **110** (represented by the horizontal axis of the graph) and the sensitivity ratio=(the sensitivity of the second photoelectric conversion portion **122**)/(the sensitivity of the first photoelectric conversion portion **121**) (represented by the vertical axis of the graph). The dash-dot line drawn in FIG. **5** represents a case where the second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** coincides with the center **126** of the second photoelectric conversion portion **122**. Accordingly, the zone on the right side with respect to the dash-dot line corresponds to a case where the end **114** is on the −X side (the first-photoelectric-conversion-portion side) with respect to the center **126**, which corresponds to the positional relationship illustrated in FIGS. **4**A and **4**B. The zone on the left side with respect to the dash-dot line corresponds to a case where the end **114** is on the +X side with respect to the center **126**. As can be seen from FIG. **5**, if the end **114** is on the +X side with respect to the center **126**, the sensitivity ratio is higher than 50%, which means there is substantially no difference in sensitivity between the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122**. Hence, the second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** may be positioned on the first-photoelectric-conversion-portion side with respect to the center **126** of the second photoelectric conversion portion **122**.

Amount of Shift of Waveguide from Viewpoint of Angular Dependence of Sensitivity

As illustrated in FIGS. **6**A and **6**B, the second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** may be positioned on the first-photoelectric-conversion-portion side with respect to a boundary **127** between the barrier region **123** and the second photoelectric conversion portion **122**. Such a configuration can further reduce the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122**.

Moreover, the second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** may be positioned on the second-photoelectric-conversion-portion side (+X side) with respect to a boundary between the barrier region **123** and the first photoelectric conversion portion **121**. If the second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** is positioned on the −X side with respect to the boundary between the barrier region **123** and the first photoelectric conversion portion **121**, substantially all rays of light emitted from the waveguide **110** enter the first photoelectric conversion portion **121**. Accordingly, the sensitivity of the second photoelectric conversion portion **122** becomes too low. Consequently, the quality of an image acquired by the second photoelectric conversion portion **122** may be deteriorated.

That is, the best position of the second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** is a position on the second-photoelectric-conversion-portion side with respect to the boundary between the barrier region **123** and the first photoelectric conversion portion **121** and on the first-photoelectric-conversion-portion side with respect to the boundary **127** between the barrier region **123** and the second photoelectric conversion portion **122**.

FIG. **6**A is a plan view (XY-plane diagram) of the pixel **101** seen from the light-entrance side (the pixel **101** seen in the direction perpendicular to the substrate **120**). FIG. **6**B is a sectional view of the pixel **101** that is taken along line VIB-VIB illustrated in FIG. **6**A. The boundary **127** between the barrier region **123** and the second photoelectric conversion portion **122** refers to a point of a plan-view shape, seen in the Z direction, of the second photoelectric conversion portion **122** that is at the surface of the substrate **120** and at the extreme end on the first-photoelectric-conversion-portion side (a point where the X coordinate is smallest in FIGS. **6**A and **6**B).

FIGS. **7**A to **7**D are graphs illustrating the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** with different amounts of shift of the waveguide **110**. The amount of shift is reduced in order of FIGS. **7**A to **7**D. FIGS. **7**A and **7**B each correspond to the arrangement illustrated in FIGS. **6**A and **6**B, in which the end **114** is positioned on the −X side, i.e., the first-photoelectric-conversion-portion side, with respect to the boundary **127**. FIGS. **7**C and **7**D each correspond to the arrangement illustrated in FIGS. **4**A and **4**B, in which the end **114** is positioned on the +X side, i.e., the second-photoelectric-conversion-portion side, with respect to the boundary **127**.

As can be seen from FIGS. **7**A to **7**D, the angular dependence of each of the photoelectric conversion portions **121** and **122** is lower in the arrangement corresponding to FIGS. **7**A and **7**B than in the arrangement corresponding to FIGS. **7**C and **7**D. That is, if the end **114** is positioned on the first-photoelectric-conversion-portion side (−X side) with respect to the boundary **127** as illustrated in FIGS. **6**A and **6**B, the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** can be reduced further.

The reason for the lower angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** in the arrangement illustrated in FIGS. **6**A and **6**B is as follows.

FIG. **8**A is a diagram schematically illustrating how a ray of light is propagated in the case where the end **114** is positioned on the second-photoelectric-conversion-portion side (+X side) with respect to the boundary **127**. As illustrated in FIG. **8**A, a ray **141** traveling in the −Z direction and toward the +X side within an angle range **140**, that is, being incident on the pixel **101** at an angle +θ, is selectively coupled with a plurality of specific waveguide modes **142** and exits from the waveguide **110** into the second photoelectric conversion portion **122**. The ray having entered the second photoelectric conversion portion **122** is converted into electrons. Most of the electrons are accumulated in the second photoelectric conversion portion **122** with the effect of a strong drift field of the second photoelectric conversion portion **122**. Therefore, the sensitivity of the second photoelectric conversion portion **122** with respect to the ray **141** that is incident on the pixel **101** at a specific angle (within the angle range **140** in FIGS. **7**A to **7**D) is increased, resulting in angular dependence.

FIG. **8**B illustrates how the ray **141** that is incident on the pixel **101** at an angle +θ is propagated in the case where the end **114** is positioned on the first-photoelectric-conversion-portion side (−X side) with respect to the boundary **127**. In this case, as in the case illustrated in FIG. **8**A, the ray **141** incident on the pixel **101** at an angle +θ is selectively coupled with the plurality of specific waveguide modes **142**, and the ray thus coupled with the waveguide modes **142**

exits from the waveguide **110**. In this case, however, the ray having exited from the waveguide **110** does not enter the second photoelectric conversion portion **122** but enters the barrier region **123**. The ray having entered the barrier region **123** is converted into photoelectrons in the barrier region **123**. The photoelectrons are diffused in the substrate **120** and are accumulated in either of the photoelectric conversion portions **121** and **122**. Therefore, the angular dependence of the sensitivity of each of the photoelectric conversion portions **121** and **122** is lower than in the case illustrated in FIG. **8**A.

That is, the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** can further be made lower in the case where the end **114** is positioned on the −X side with respect to the boundary **127** than in the case where the end **114** is positioned on the +X side with respect to the boundary **127**.

As can be seen from the comparison between the case illustrated in FIGS. **7**C and **7**D and the case illustrated in FIG. **17**C, even if the end **114** is positioned on the second-photoelectric-conversion-portion side with respect to the boundary **127**, the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** is lower than that observed in the related-art solid-state image sensor. This is because even the ray that has been coupled with a plurality of specific waveguide modes **142** exhibits a more even distribution of light intensity at the exit face **111**E of the waveguide **110** than in the case where light is condensed with a microlens.

Supplementary Explanation

The areas of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** may be different as illustrated in FIGS. **2**A to **2**C or the same. Even if the photoelectric conversion portions **121** and **122** have the same aperture area, the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** can have different levels of sensitivity, as long as the center **113** of the exit face **111**E of the core **111** is shifted with respect to the center **124** of the barrier region **123**.

If the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** are arranged side by side in the XY plane and in a direction that is at an angle β (>0°) with respect to the X axis, the center **113** of the exit face **111**E of the core **111** is shifted along the surface of the substrate **120** with respect to the center **124** of the barrier region **123** and in a direction that is at the angle β with respect the X axis.

Protective Layer and Angular Dependence

Now, the thickness of the protective layer **116** will be described.

FIGS. **9**A to **9**D are graphs illustrating the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** with different values of optical distance L between the exit face **111**E of the core **111** and the surface of the substrate **120**, i.e., with different thicknesses t of the protective layer **116**. The optical distance L refers to an actual distance t multiplied by a refractive index n of the protective layer **116**, which is expressed as L=n*t. If the protective layer **116** includes a plurality of different layers, the optical distance L is the sum of values each being the actual distance of a corresponding one of the layers that is multiplied by the refractive index of that layer.

The optical distance L increases in order of FIGS. **9**A to **9**D.

FIGS. **9**A and **9**B illustrate cases where L/λ is 0.5 and 1.5, respectively. The value L/λ is obtained by dividing the optical distance L by a center wavelength λ of light that is sensible by the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122**. FIGS. **9**C and **9**D illustrate cases where L/λ is 2.6 and 3.8, respectively. As can be seen from FIGS. **9**A to **9**D, the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** is lower in the cases illustrated in FIGS. **9**A and **9**B than in the cases illustrated in FIGS. **9**C and **9**D particularly in an angle range **140**.

That is, the distance between the exit face **111**E of the core **111** and a light-entrance-side surface of the substrate **120** may be short. Specifically, the optical distance L between the exit face **111**E of the core **111** and the surface of the substrate **120** may be set to twice the wavelength of light that is sensible by the photoelectric conversion portions **121** and **122** or shorter. Herein, the case where the light is sensible by the photoelectric conversion portions **121** and **122** refers to a case where 5% or more of the light that is incident on the pixel **101** is absorbed by a combination of the photoelectric conversion portions **121** and **122**.

The reason for the above is as follows. As described above, a ray that is incident on the pixel **101** at an angle within the angle range **140** is selectively coupled with a plurality of specific waveguide modes **142**. Then, the ray exits from the exit face **111**E of the core **111** and is coupled with a specific propagation mode in the protective layer **116**. Hence, if the distance between the exit face **111**E of the core **111** and the surface of the substrate **120** is long, the ray exited from the exit face **111**E of the core **111** is propagated within the protective layer **116** before reaching the surface of the substrate **120**. A portion of the ray propagated in such a manner enters the second photoelectric conversion portion **122** and is converted into electric charge. Most of such electric charge is accumulated in the second photoelectric conversion portion **122**. Therefore, the sensitivity of the second photoelectric conversion portion **122** for the ray that is incident on the pixel **101** at a specific angle is increased, resulting in angular dependence of sensitivity.

Comparing FIGS. **9**C and **9**D with FIG. **17**C, the angular dependence of the sensitivity is lower than that observed in the related-art solid-state image sensor even if the optical distance L between the exit face **111**E of the waveguide **110** and the surface of the substrate **120** is longer than twice the wavelength of the light that is sensible by the photoelectric conversion portions **121** and **122**. This is because, as described above, the intensity distribution, at the exit face **111**E of the waveguide **110**, of the light coupled with the plurality of specific waveguide modes **142** is also more even than that of the light condensed by the microlens.

The distribution of refractive index of the protective layer **116** in a region directly below the exit face **111**E of the core **111** may be even in the in-plane direction of the substrate **120** (in the XY plane). If the refractive index of the protective layer **116** varies in the in-plane direction, the propagation mode of the ray having exited from the waveguide **110** with a nearly even distribution is changed by the refractive-index variation in the XY direction before the ray reaches the surface of the substrate **120**. Consequently, the angular dependence of the sensitivity of each of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** is increased. The state where the distribution of refractive index is even refers to a state where the standard deviation of the distribution of refractive index is 0.1 or lower.

The distribution of refractive index of the protective layer **116** is obtained by measuring the refractive index of the protective layer **116** in the region directly below the exit face **111**E of the core **111** at five or more points on a line connecting the respective centroids of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122**, including a point on the barrier region **123** and a point on the first photoelectric conversion portion **121**. The points of measurement are all at the same distance from the surface of the substrate **120** in the thickness direction. Specifically, if the protective layer **116** includes a plurality of layers, the refractive index is measured within one layer.

The refractive index is measurable with an interferometer, an ellipsometer, or the like. Alternatively, the composition of the material for the protective layer **116** may first be analyzed by Fourier-transform infrared spectroscopy (FTIR), x-ray diffractometry (XRD), mass analysis, or the like, and the result may be converted into refractive index.

Shape and Position of Waveguide

The shape of the waveguide **110** according to the general embodiment of the present invention is not limited to the shape illustrated in FIGS. **2**A and **2**B, as long as the center **113** of the exit face **111**E of the core **111** is shifted toward the first-photoelectric-conversion-portion side (−X side) with respect to the center **124** of the barrier region **123** at the surface of the substrate **120**. For example, as illustrated in FIG. **10**A, seen in the direction (Z direction) perpendicular to the surface of the substrate **120**, a center **115** of an entrance face of the core **111** may coincide with the center **113** of the exit face **111**E of the core **111**. Alternatively, as illustrated in FIG. **10**B, the center **115** of the entrance face of the core **111** may be positioned on the second-photoelectric-conversion-portion side (+X direction) with respect to the center **113** of the exit face **111**E of the core **111** in the in-plane direction (XY direction) of the substrate **120**. Moreover, as illustrated in FIG. **10**C, a part of the core **111** of the waveguide **110** may extend over an adjacent pixel **101**. Note that, to avoid the occurrence of crosstalk between adjacent pixels **101**, a first-photoelectric-conversion-portion-side end of the exit face **111**E of the core **111** may be prevented from being positioned over an adjacent pixel **101**. The first-photoelectric-conversion-portion-side end of the exit face **111**E of the core **111** refers to a point of a plan-view shape, seen in the Z direction, of the exit face **111**E of the core **111** that is at the extreme end on the first-photoelectric-conversion-portion side (a point where the X coordinate is smallest in FIGS. **10**A to **10**C).

Furthermore, "the center **115** of the entrance face of the core **111**" refers to the centroid of a plan-view shape, seen in the Z direction, of the entrance face of the core **111**, as with "the center **113** of the exit face **111**E of the core **111**."

The structure illustrated in FIG. **10**A can be fabricated relatively easily. In the structure illustrated in FIG. **10**B or **10**C, it is easier to position the second-photoelectric-conversion-portion-side end **114** of the exit face **111**E of the core **111** on the first-photoelectric-conversion-portion side (−X side) with respect to the boundary **127** between the barrier region **123** and the second photoelectric conversion portion **122**. The waveguide **110** illustrated in FIG. **10**B can be formed by performing etching after providing sacrificial layers having different thicknesses or by performing multi-stage etching while providing openings of different sizes.

The plan-view shape of the core **111** is not limited to the circular shape as illustrated in FIG. **2**A and may be an elliptical or polygonal shape. The corners of the polygonal shape may be rounded in a manufacturing process.

Microlens

A microlens may be provided on the light-entrance side with respect to the waveguide **110**. If a microlens is provided, light that is incident on the pixel **101** can be efficiently guided to the waveguide **110**. Note that, if a microlens is provided, the angular dependence of the sensitivity of a region between the photoelectric conversion portions **121** and **122** is increased. Therefore, from the viewpoint of reducing the angular dependence, the microlens is not necessary. However, even if a microlens is provided, the angular dependence of each of the photoelectric conversion portions **121** and **122** is lower than that observed in the related-art solid-state image sensor, because of the following reason.

If no waveguide is provided between the microlens and the photoelectric conversion portions as in the related-art solid-state image sensor, the focusing effect of the microlens directly affects the angular dependence of the sensitivity of the photoelectric conversion portions. In contrast, if a waveguide is provided between the microlens and the photoelectric conversion portions, light transmitted through the microlens is incident on the entrance face of the waveguide. The light thus incident on the entrance face of the waveguide is propagated in the waveguide while being coupled with a plurality of waveguide modes, and is emitted toward the photoelectric conversion portions. Therefore, the distribution of light intensity is more even at the exit face of the waveguide than at the entrance face of the waveguide. That is, the distribution of light intensity can be made more even than in the case of the related-art solid-state image sensor in which light that is incident on the pixel is condensed on the photoelectric conversion portions while being transmitted only through the microlens. Hence, according to the general embodiment of the present invention, even if a microlens is provided on the light-entrance side with respect to the waveguide **110**, the angular dependence of the photoelectric conversion portions **121** and **122** can be made lower than that observed in the related-art solid-state image sensor.

FIG. **11**A illustrates an exemplary case where a microlens **117** is provided on the uppermost surface of the pixel **101**. FIG. **11**B illustrates an exemplary case where a microlens **117** is provided between the waveguide **110** and the uppermost surface of the pixel **101**. In this case, the microlens **117** is made of the same material as the core **111**. FIG. **11**C illustrates an exemplary case where microlenses **117-1** and **117-2** are provided on the uppermost surface of the pixel **101** and between the waveguide **110** and the uppermost surface of the pixel **101**, respectively. The microlenses **117** may each be made of an inorganic material such as silicon oxide, silicon nitride, silicon oxynitride, silicon carbide, or BPSG, or an organic material such as polymer or resin.

Microlens Having Different Levels of Refractive Power in Different Directions

As illustrated in FIGS. **12**A to **12**D, if a microlens **117** having different levels of refractive power in the X and Y directions is used, the sensitivity of the photoelectric conversion portions **121** and **122** can be increased while the angular dependence of the sensitivity ratio is reduced. FIG. **12**A illustrates an outline layout of a pixel **101** in the XY plane (a layout of the pixel **101** that is seen in the direction perpendicular to the substrate **120**). FIGS. **12**B to **12**D each include an X-Z sectional diagram taken along line A-A illustrated in FIG. **12**A on the left side and a Y-Z sectional diagram taken along line B-B illustrated in FIG. **12**A on the right side.

If the refractive power of the microlens **117** in a first direction (along line A-A) in which the line connecting the center of the first photoelectric conversion portion **121** and

the center of the second photoelectric conversion portion **122** to each other extends is high, the distribution of light intensity in the first direction at the entrance face of the waveguide **110** greatly depends on the angle of incidence of the light on the pixel **101** in the first direction. As the first-direction distribution of light intensity at the entrance face of the waveguide **110** becomes more uneven, the first-direction distribution of intensity of the light exiting from the waveguide **110** becomes more uneven. Accordingly, the ratio between the quantities of light that enters the respective photoelectric conversion portions **121** and **122** changes. Thus, if the refractive power of the microlens in the first direction is high, the angular dependence of each of the photoelectric conversion portions **121** and **122** in the first direction is high.

In contrast, the refractive power of the microlens **117** in a second direction (along line B-B) perpendicular to the first direction at the surface of the substrate **120** (in the XY plane) only affects the second-direction distribution of intensity of the light exiting from the waveguide **110**. The first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** are provided side by side in the first direction. Therefore, even if the intensity distribution is uneven in the second direction, the change in the ratio between the quantities of light that enters the respective photoelectric conversion portions **121** and **122** is small.

In view of the above, the refractive power of the microlens **117** in the X direction that greatly affects the angular dependence of sensitivity may be reduced, whereas the refractive power of the microlens **117** in the Y direction that little affects the angular dependence of sensitivity may be increased, considering the sensitivity of the photoelectric conversion portions **121** and **122**. That is, in the XY plane, the microlens **117** may have a lower refractive power in the first direction in which the line connecting the center of the first photoelectric conversion portion **121** and the center of the second photoelectric conversion portion **122** are connected to each other than in the second direction that is perpendicular to the first direction. Particularly, if the focal point of the microlens **117** in the second direction is defined near the entrance face of the core **111**, the sensitivity of the photoelectric conversion portions **121** and **122** is maximized.

In each of the cases illustrated in FIGS. **12**A to **12**D, the first direction of the microlens **117** corresponds to the X direction, and the second direction of the microlens **117** corresponds to the Y direction. FIG. **12**B illustrates a case where the radius of curvature of the light-entrance face of the microlens **117** in the XZ section is larger than that in the YZ section. FIG. **12**C illustrates a case where the refractive power in the X direction is zero, that is, a case of a cylindrical lens whose axis extends in the X direction. FIG. **12**D illustrates a case of a digital lens **118** which has a plurality of microscopic structures each having a size of about 1/10 of the wavelength or small arranged such that the refractive power in the X direction is lower than the refractive power in the Y direction, whereby the refractive-index distributions in the X direction and in the Y direction are controlled independently of each other.

The above description all concerns a front-side-illuminated solid-state image sensor in which the wiring lines **125** are provided on the same side of the substrate **120** as the waveguide **110**. Alternatively, the solid-state image sensor may be of a back-side-illuminated type in which the wiring lines **125** are provided on the other side of the substrate **120** across from the waveguide **110**. If the present invention is applied to a back-side-illuminated solid-state image sensor, the layout of the waveguide **110** and the layout of the wiring lines **125** can be determined independently of each other. Therefore, the manufacturing process is simplified. Particularly, if a part of the waveguide **110** extends over an adjacent pixel **101** as illustrated in FIG. **10**C, the solid-state image sensor may be of the back-side-illuminated type, because the flexibility in the layout of wiring lines **125** in the front-side-illuminated type is limited by the presence of the waveguide **110**.

Arrangement of Pixels in Pixel Area

In the case where a plurality of pixels **101** are provided in the pixel area **103** of the solid-state image sensor **100**, the arrangement of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** in a single pixel **101** may be the same for all of the plurality of pixels **101** or different between different pixels **101**.

Note that, if a part of the waveguide **110** extends over an adjacent pixel **101** as illustrated in FIG. **10**C, an arrangement illustrated in FIG. **13**A or **13**B may be employed, because the cores **111** of the waveguides **110** of adjacent pixels **101** are prevented from interfering with each other.

FIG. **13**A illustrates a case where the direction from the center of the first photoelectric conversion portion **121** toward the center of the second photoelectric conversion portion **122** in a single pixel **101** is the +X direction for all of the pixels **101**. FIG. **13**B illustrates a case where the direction from the center of the first photoelectric conversion portion **121** toward the center of the second photoelectric conversion portion **122** in a single pixel **101** is opposite between pixels **101** that are adjacent to each other in the direction orthogonal to the line connecting the center of the first photoelectric conversion portion **121** and the center of the second photoelectric conversion portion **122** to each other. In FIGS. **13**A and **13**B, the first direction of each pixel **101** is the same for all of the pixels **101**, and the second direction is therefore the same for both of the adjacent pixels **101**.

The direction from the center of the first photoelectric conversion portion **121** toward the center of the second photoelectric conversion portion **122** in a single pixel **101** may be different between different pixels **101**. That is, the direction may be the X direction in some pixels **101**, the Y direction in other pixels **101**, and a direction that is oblique with respect to the X direction in yet other pixels **101**.

First Embodiment

A first embodiment of the present invention will now be described with reference to FIG. **1** and FIGS. **2**A to **2**C. In the first embodiment, the solid-state image sensor according to the present invention is used for forming an image with a wide dynamic range by acquiring a high-sensitivity signal and a low-sensitivity signal and combining the two together.

In the first embodiment, a high-sensitivity signal is acquired by the first photoelectric conversion portion **121**, which receives a larger portion of the light, and a low-sensitivity signal is acquired by the second photoelectric conversion portion **122**, which receives a smaller portion of the light. The photoelectric conversion portions **121** and **122** are driven by receiving the respective signals transmitted from the peripheral circuits **104** through the wiring lines **125** and in such a manner as to be exposed to light for the same period of time.

The signals acquired by the respective photoelectric conversion portions **121** and **122** are transferred to the peripheral circuits **104** through the wiring lines **125** and are output from the peripheral circuits **104** to an external device. The

signals acquired by the photoelectric conversion portions **121** and **122** may be output from the peripheral circuits **104** as they are. Alternatively, a high-sensitivity signal may be output if the quantity of light that is incident on the pixel **101** is smaller than a threshold, and a low-sensitivity signal may be output if the quantity of light that is incident on the pixel **101** is larger than or equal to the threshold. The threshold is set to a value smaller than a value corresponding to the signal intensity at which the high-sensitivity signal is saturated and larger than a value corresponding to the signal intensity at which the low-sensitivity signal exhibits a desired signal-to-noise (SN) ratio.

Now, a method of widening the dynamic range by using the high-sensitivity signal and the low-sensitivity signal will be described. FIGS. **14**A to **14**C are graphs illustrating the dependence of the intensity of each of a high-sensitivity signal **1031** and a low-sensitivity signal **1032** upon the quantity of light that is incident on the pixel **101** per unit time. As illustrated in FIG. **14**A, if the intensity of the high-sensitivity signal **1031** is lower than or equal to a first threshold **1051**, the high-sensitivity signal **1031** is used. If the intensity of the low-sensitivity signal **1032** is higher than or equal to a second threshold **1052**, the low-sensitivity signal **1032** is used. With a combination of the two signals **1031** and **1032**, an image with a wide dynamic range is acquired.

The first threshold **1051** is set to a signal intensity lower than the signal intensity at which the high-sensitivity signal **1031** is saturated. The second threshold **1052** is set to a signal intensity at which the SN ratio of the low-sensitivity signal **1032** exceeds a desired value. Hence, a quantity **1062** of light incident on the pixel **101** when the intensity of the low-sensitivity signal **1032** is equal to the second threshold **1052** needs to be smaller than a quantity **1061** of light incident on the pixel **101** when the intensity of the high-sensitivity signal **1031** is equal to the first threshold **1051**.

Here, let us consider the case of the related-art solid-state image sensor illustrated in FIGS. **17**A to **17**C. As can be seen from FIG. **17**C, the angular dependence of the sensitivity ratio between the photoelectric conversion portions **1021** and **1022** is particularly high in the angle range **1040**. Therefore, the sensitivity ratio between the photoelectric conversion portions **1021** and **1022** changes with the states of the image pickup lens and the aperture that are used. Consequently, image quality may be deteriorated, or the dynamic range may be narrowed. The mechanism of such a situation is as follows.

FIG. **14**B illustrates a case where the sensitivity ratio between the first photoelectric conversion portion **1021** and the second photoelectric conversion portion **1022** is high because the image pickup lens used has a large f-number or the size of the aperture is reduced. This case corresponds to, for example, a case where light at an angle within the angle range **1041** indicated in FIG. **17**C is incident on the pixel **101**.

In such a case, the quantity **1062** of light incident on the pixel **101** when the intensity of the low-sensitivity signal **1032** is equal to the second threshold **1052** is larger than the quantity **1061** of light incident on the pixel **101** when the intensity of the high-sensitivity signal **1031** is equal to the first threshold **1051**. Therefore, if the quantity of light incident on the pixel **101** is within a range **1063**, the high-sensitivity signal **1031** is saturated while the low-sensitivity signal **1032** has an insufficient SN ratio. Hence, the quality of an image composed may be deteriorated in the range **1063** corresponding to the point of switching between the high-sensitivity signal **1031** and the low-sensitivity signal **1032**. The signal is saturated when the quantity of light that is incident on the photoelectric conversion portion exceeds a level at which the amount of charge accumulated in the photoelectric conversion portion reaches the maximum.

Now, let us consider a case where the sensitivity ratio between the first photoelectric conversion portion **1021** and the second photoelectric conversion portion **1022** is low. FIG. **14**C illustrates the case where the sensitivity ratio between the first photoelectric conversion portion **1021** and the second photoelectric conversion portion **1022** is low because the lens used has a small f-number or the aperture is fully opened. This case corresponds to, for example, a case where light within an angle range **1042** indicated in FIG. **17**C is incident on the pixel **101**. In such a case, the quantity of light that is required for the acquisition of a desired SN ratio in the first photoelectric conversion portion **1021** is larger than in the case illustrated in FIG. **14**A. In addition, the second photoelectric conversion portion **1022** is saturated with a smaller quantity of light than in the case illustrated in FIG. **14**A. Consequently, the dynamic range of an image composed is narrowed by a range **1064** in which the intensity of the high-sensitivity signal **1031** is lower than the second threshold **1052** and another range **1064** in which the low-sensitivity signal **1032** is saturated.

As described above, if the angular dependence of the sensitivity ratio between the photoelectric conversion portions **1021** and **1022** is high, the quality of a resulting image may be deteriorated at the point of switching between the two signals or the dynamic range may be narrowed, depending on the states of the lens and the aperture that are used for applying light to the solid-state image sensor. In contrast, in the solid-state image sensor **100** according to the first embodiment of the present invention, the angular dependence of the sensitivity of each of the photoelectric conversion portions **121** and **122** having different levels of sensitivity is low, as typically graphed in FIG. **3**. Therefore, in addition to the above-mentioned reduction in the distortion of a defocused image, an image with an SN ratio that is higher than or equal to the desired level and with a wide dynamic range is acquired.

The required sensitivity ratio between the photoelectric conversion portions **121** and **122** is determined on the basis of the dynamic range or the SN ratio that is required for an image to be composed. In the first embodiment, the amount of shift of the center **113** of the exit face **111**E of the core **111** with respect to the center **124** of the barrier region **123** may be determined on the basis of the dynamic range or the SN ratio that is required for an image to be composed.

To widen the dynamic range by combining the two signals, the following relationship needs to be satisfied:

$$C1/S1 > C2/S2 \qquad \text{(Expression 1)}$$

where S**1** and C**1** denote the sensitivity and the capacity, respectively, of the first photoelectric conversion portion **121** that acquires the high-sensitivity signal, and S**2** and C**2** denote the sensitivity and the capacity, respectively, of the second photoelectric conversion portion **122** that acquires the low-sensitivity signal.

The reason for this is as follows. If $C1/S1 \leq C2/S2$, the first photoelectric conversion portion **121** that acquires the high-sensitivity signal is saturated with a quantity of light that is smaller than or equal to the quantity of light with which the second photoelectric conversion portion **122** that acquires the low-sensitivity signal is saturated. Moreover, C**1**/S**1** may be twice the C**2**/S**2** or larger. Note that C**1**/S**1** and C**2**/S**2** are each the maximum quantity of light that may be accumu-

lated as charge in a corresponding one of the photoelectric conversion portions **121** and **122**.

The ratio between the sensitivity S1 of the first photoelectric conversion portion **121** and the sensitivity S2 of the second photoelectric conversion portion **122** is changeable with the amount of shift of the center **113** of the exit face **111**E of the core **111** with respect to the center **124** of the barrier region **123**, as described above.

To increase the capacity C1 or C2 of the photoelectric conversion portion **121** or **122**, the volume of the photoelectric conversion portion **121** or **122** or the concentration of a dopant for forming the photoelectric conversion portion **121** or **122** may be increased. To increase the volume of the photoelectric conversion portion **121** or **122**, the opening of the photoelectric conversion portion **121** or **122** may be widened by increasing the area of ion implantation, or the depth of the photoelectric conversion portion **121** or **122** may be increased by implanting ions deeply into the substrate **120**. Note that, if the photoelectric conversion portions **121** and **122** have the same depth and the same dopant concentration, the photoelectric conversion portions **121** and **122** can be formed under the same ion-implantation conditions, whereby the manufacturing process is simplified.

Even if the exposure time for the first photoelectric conversion portion **121** and the exposure time for the second photoelectric conversion portion **122** are not the same, an image with a wide dynamic range can be acquired, as long as the amounts of charge that may be accumulated in the respective photoelectric conversion portions **121** and **122** are different. However, if the exposure time for the first photoelectric conversion portion **121** and the exposure time for the second photoelectric conversion portion **122** are different, the photoelectric conversion portions **121** and **122** particularly cause different levels of motion blur of the object. An image composed in such a manner may appear unnatural. Therefore, the exposure time for the first photoelectric conversion portion **121** and the exposure time for the second photoelectric conversion portion **122** are desired to be the same.

The pixel **101** may include three or more photoelectric conversion portions having different levels of sensitivity. If pixel signals acquired by three or more photoelectric conversion portions having different levels of sensitivity are combined, the dynamic range of an image to be composed can be widened further.

Second Embodiment

A second embodiment of the present invention will now be described. In the second embodiment, the solid-state image sensor according to the present invention is used such that a plurality of photoelectric conversion portions having different levels of sensitivity are driven for different periods of exposure time, whereby an image taken with low sensitivity and a long exposure time and an image taken with high sensitivity and a short exposure time are acquired simultaneously.

In general, the exposure time required for taking a smooth moving image often becomes longer than the exposure time required for taking a still image. Hereinafter, an image taken with low sensitivity and a long exposure time is regarded as a moving image, and an image taken with high sensitivity and a short exposure time is regarded as a still image. If the exposure time for the still image is longer than the exposure time for the moving image, the photoelectric conversion portions provided for acquiring the moving image and the still image, respectively, only need to be interchanged with each other.

The second embodiment is different from the first embodiment in that the exposure time for the first photoelectric conversion portion **121** is shorter than the exposure time for the second photoelectric conversion portion **122**. The first photoelectric conversion portion **121** acquires a still-image signal, and the second photoelectric conversion portion **122** acquires a moving-image signal. The signals thus acquired are output from the peripheral circuits **104** and are used for forming a still image and a moving image, respectively.

Let us consider a case of the related-art solid-state image sensor illustrated in FIGS. **17**A to **17**C. As can be seen from FIG. **17**C, the angular dependence of the sensitivity ratio between the photoelectric conversion portions **1021** and **1022** is particularly high in the angle range **1040**. Therefore, the sensitivity of each of the photoelectric conversion portions **1021** and **1022** changes with the states of the lens and the aperture that are used. Consequently, the quality of a resulting still image and a resulting moving image may be deteriorated.

For example, if the lens used has a large f-number or the size of the aperture is reduced, the incident angle of the light that enters the pixel **1001** is within the angle range **1041** indicated in FIG. **17**C. In the angle range **1041**, the sensitivity of the first photoelectric conversion portion **1021** is high, and the sensitivity of the second photoelectric conversion portion **1022** is low. Consequently, the first photoelectric conversion portion **1021** is easily saturated, and overexposure tends to occur in a resulting still image. In addition, the insufficiency in the sensitivity of the second photoelectric conversion portion **1022** tends to cause underexposure in a resulting moving image.

For example, if the lens used has a small f-number or the aperture is fully opened, the incident angle of the light that enters the pixel **1001** is within the angle range **1040** indicated in FIG. **17**C. In the angle range **1040**, the sensitivity of the first photoelectric conversion portion **1021** is low, and the sensitivity of the second photoelectric conversion portion **1022** is high. Consequently, the sensitivity of the first photoelectric conversion portion **1021** becomes insufficient, and underexposure tends to occur in a resulting still image. In addition, the second photoelectric conversion portion **1022** is easily saturated, and overexposure tends to occur in a resulting moving image.

As described above, if the angular dependence of the sensitivity of each of the photoelectric conversion portions is high, the quality of a resulting still image and a resulting moving image may be deteriorated, depending on the states of the lens and the aperture that are used.

In contrast, in the solid-state image sensor **100** according to the second embodiment of the present invention, the angular dependence of the sensitivity of each of the photoelectric conversion portions **121** and **122** having different levels of sensitivity is low, as typically graphed in FIG. **3**. Therefore, in addition to the above-mentioned reduction in the distortion of a defocused image, a moving image and a still image that are of high quality can be acquired simultaneously, regardless of the states of the lens and the aperture that are used.

With the solid-state image sensor **100** according to the second embodiment, different images, i.e., a still image and a moving image, can be formed from the still-image signal acquired by the first photoelectric conversion portion **121** and the moving-image signal acquired by the second pho-

toelectric conversion portion **122**, respectively. Therefore, the still-image signal and the moving-image signal may be generated with respective levels of intensity that are as close to each other as possible and with respective dynamic ranges that are as close to each other as possible.

Hence, the following relationships may also be satisfied:

$$S1\times T1=S2\times T2 \quad \text{(Expression 2)}$$

$$C1/(S1\times T1)=C2/(S2\times T2) \quad \text{(Expression 3)}$$

where **S1**, **C1**, and **T1** denote the sensitivity, the capacity, and the exposure time, respectively, of the first photoelectric conversion portion **121** that acquires the still-image signal, and **S2**, **C2**, and **T2** denote the sensitivity, the capacity, and the exposure time, respectively, of the second photoelectric conversion portion **122** that acquires the moving-image signal.

Expression 2 defines a condition regarding the signal intensity. Expression 3 defines a condition regarding the dynamic range.

As described above, the ratio between **S1** and **S2** is controllable by changing the amount of shift of the waveguide **110**. As can be seen from Expression 2, in the second embodiment, the ratio between **S1** and **S2** can be determined by estimating the exposure time for each of a still image and a moving image to be used. For example, if the exposure time for the moving image is 1/60 seconds and the exposure time for the still image is 1/600 seconds, the pixel **101** is configured such that **S1** is ten times **S2**.

To satisfy Expressions 2 and 3 simultaneously, the capacity **C1** of the first photoelectric conversion portion **121** and the capacity **C2** of the second photoelectric conversion portion **122** may be the same. Herein, "to be the same" implies that errors due to tolerances in the manufacturing process are permissible. Specifically, if the difference between the capacity **C1** of the first photoelectric conversion portion **121** and the capacity **C2** of the second photoelectric conversion portion **122** is smaller than 10% of the capacity **C1** of the first photoelectric conversion portion **121**, the capacities **C1** and **C2** are regarded as being the same.

As described above, the capacity of the photoelectric conversion portion is determined by the volume of the photoelectric conversion portion and the concentration of the dopant for forming the photoelectric conversion portion. FIGS. **15**A and **15**B illustrate different cases in each of which the capacity of the first photoelectric conversion portion **121** and the capacity of the second photoelectric conversion portion **122** are the same. FIGS. **15**A and **15**B each include, on the left side, an XY plan view of the pixel **101** that illustrates the layout at the surface of the substrate **120** seen in the Z direction (a plan view of the pixel **101** that is seen in the direction perpendicular to the substrate **120**) and, on the right side, an XZ sectional view of the pixel **101** that is taken along line A-A illustrated in the XY plan view. In either case, the center **113** of the exit face **111**E of the core **111** is shifted toward the first-photoelectric-conversion-portion side (−X side) with respect to the center **124** of the barrier region **123**.

In the case illustrated in FIG. **15**A, the X-direction length of the first photoelectric conversion portion **121** is longer than the X-direction length of the second photoelectric conversion portion **122**, and the Z-direction depth of the first photoelectric conversion portion **121** is greater than the Z-direction depth of the second photoelectric conversion portion **122**. In the case illustrated in FIG. **15**B, the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** have the same X-direction length, the same Z-direction depth, and the same dopant concentration. If the photoelectric conversion portions **121** and **122** have the same depth and the same dopant concentration, the photoelectric conversion portions **121** and **122** can be formed under the same ion-implantation conditions, whereby the manufacturing process is simplified. Hence, in terms of the manufacturing process, the configuration illustrated in FIG. **15**B is superior.

The pixel **101** may include three or more photoelectric conversion portions. If the exposure time is varied among the three or more photoelectric conversion portions and three or more images based on the respectively different periods of exposure time are acquired simultaneously, a plurality of images having different levels of blur can be acquired. Moreover, photoelectric conversion portions to be used may be selected in accordance with the shutter speed that is set. According to Expressions 2 and 3, suitable characteristics of the photoelectric conversion portions vary with the set shutter speed. Hence, if two of the three or more photoelectric conversion portions are selected, a still-image signal and a moving-image signal with close levels of intensity and close dynamic ranges can be acquired simultaneously.

Signals acquired by a plurality of photoelectric conversion portions exposed to light for the same period of time may be used for the acquisition of an image with a wide dynamic range, and signals acquired by a plurality of photoelectric conversion portions exposed to light for different periods of time may be used for the simultaneous acquisition of a still image and a moving image.

Third Embodiment

FIG. **16** is a schematic diagram illustrating an image pickup apparatus **190** including the solid-state image sensor **100** according to any of the embodiments of the present invention. The image pickup apparatus **190** includes a housing **197** having a lens attaching portion **196** to which an image pickup lens **191** is attached, the solid-state image sensor **100**, a control section **198** that controls the operation of the image pickup apparatus **190**, and the image pickup lens **191** that takes light from the outside into the housing **197**. The image pickup lens **191** is attached to the lens attaching portion **196** of the housing **197**. The image pickup lens **191** of the image pickup apparatus **190** may be removable from the housing **197**, i.e., interchangeable, or may be uninterchangeable. The control section **198** includes a central processing unit (CPU) **192**, a transfer circuit **193**, a signal processing unit **194**, and a device driving circuit **195**.

The CPU **192** is a circuit that controls the transfer circuit **193**, the signal processing unit **194**, and the device driving circuit **195**. The device driving circuit **195** is a circuit that drives the solid-state image sensor **100** in accordance with the signal from the CPU **192** and controls, for example, the periods of exposure time for the respective photoelectric conversion portions **121** and **122** provided in each of the pixels **101**, and the timings of reading the signals acquired by the photoelectric conversion portions **121** and **122**. The transfer circuit **193** stores the signals read from the solid-state image sensor **100** and transfers the signals to the signal processing unit **194**. The signal processing unit **194** processes the signals acquired through the transfer circuit **193** into an image.

The image pickup apparatus **190** is selectively operable in a dynamic-range-widening mode in which the solid-state image sensor **100** is driven in accordance with the first embodiment or in a moving-image-and-still-image-simulta-

neous-acquisition mode in which the solid-state image sensor **100** is driven in accordance with the second embodiment. The mode is selectable by a user through an operation unit (not illustrated). The CPU **192** controls the associated circuits in accordance with the mode selected.

If the dynamic-range-widening mode is selected, the solid-state image sensor **100** is activated such that the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** are exposed to light for the same period of time and such that the first photoelectric conversion portion **121** having higher sensitivity acquires a high-sensitivity signal and the second photoelectric conversion portion **122** having lower sensitivity acquires a low-sensitivity signal. If the quantity of light that is incident on the pixel **101** is lower than the threshold, the high-sensitivity signal is used. If the quantity of light that is incident on the pixel **101** is higher than or equal to the threshold, the low-sensitivity signal is used. With a combination of the two signals, an image with a wide dynamic range is formed.

If the moving-image-and-still-image-simultaneous-acquisition mode is selected, the solid-state image sensor **100** is activated such that the exposure time for the first photoelectric conversion portion **121** is shorter than the exposure time for the second photoelectric conversion portion **122**. If the exposure time is set to a shorter value for the still image than for the moving image for the purpose of, for example, shooting an object that is moving fast, a still-image signal is acquired by the first photoelectric conversion portion **121** having higher sensitivity while a moving-image signal is acquired by the second photoelectric conversion portion **122** having lower sensitivity. If the exposure time is set to a shorter value for the still image than for the moving image for the purpose of, for example, intentionally adding motion blur, a moving-image signal is acquired by the first photoelectric conversion portion **121** having higher sensitivity while a still-image signal is acquired by the second photoelectric conversion portion **122** having lower sensitivity. The exposure time for the still image is determined by the user. The exposure time for the moving image is set to about the value corresponding to the frame rate of the solid-state image sensor **100**. Thus, a still image and a moving image can be formed simultaneously from the still-image signal and the moving-image signal acquired in the above manner.

The solid-state image sensor **100** of the image pickup apparatus **190** is not limited to operate on the basis of only one of the first embodiment and the second embodiment. For example, the solid-state image sensor **100** may have both the mode for acquiring an image with a wide dynamic range and the mode for simultaneously acquiring a moving image and a still image so that the mode is switched between the two in accordance with the image to be acquired. In such a case, the levels of sensitivity and the capacities of the first photoelectric conversion portion **121** and the second photoelectric conversion portion **122** need to satisfy at least Expression 1. In addition, Expressions 2 and 3 may also be satisfied.

If both Expressions 2 and 3 are satisfied, the capacity of the first photoelectric conversion portion **121** and the capacity of the second photoelectric conversion portion **122** are the same. Therefore, Expression 1 is naturally satisfied. Hence, in the solid-state image sensor **100** having both the mode for acquiring an image with a wide dynamic range and the mode for simultaneously acquiring a moving image and a still image, the capacity of the first photoelectric conversion portion **121** and the capacity of the second photoelectric conversion portion **122** may be the same.

To summarize, the image pickup apparatus **190** according to the third embodiment is capable of acquiring an excellent image with a wide dynamic range and is also capable of simultaneously acquiring a moving image and a still image.

According to any of the embodiments of the present invention, a solid-state image sensor is provided in which the angular dependence of the sensitivity of each of a plurality of photoelectric conversion portions provided in each pixel and having different levels of sensitivity is reduced, and the deterioration of image quality that may occur depending on the states of a camera lens and an aperture that are used is suppressed.

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

This application claims the benefit of Japanese Patent Application No. 2015-024485, filed Feb. 10, 2015, which is hereby incorporated by reference herein in its entirety.

What is claimed is:

1. A solid-state image sensor comprising:

pixels provided in a pixel area,

the pixels each including

a first photoelectric conversion portion and a second photoelectric conversion portion that are provided in a substrate, the second photoelectric conversion portion having lower sensitivity than the first photoelectric conversion portion;

a barrier region provided between the first photoelectric conversion portion and the second photoelectric conversion portion;

a waveguide provided on a light-entrance side of the substrate and including a core and a cladding; and

a protective layer provided between the waveguide and the substrate,

wherein, when a surface of the substrate is seen in a direction perpendicular to the substrate, a center of an exit face of the core is positioned on a first-photoelectric-conversion-portion side with respect to a center of the barrier region at the surface of the substrate in each of pixels that are provided in a central part of the pixel area, and

wherein a standard deviation of a distribution of refractive index of the protective layer in a region directly below the exit face of the core is 0.1 or smaller in an in-plane direction of the substrate.

2. A solid-state image sensor according to claim **1**, wherein, when the surface of the substrate is seen in the direction perpendicular to the substrate, a second-photoelectric-conversion-portion-side end of the exit face of the core is positioned on the first-photoelectric-conversion-portion side with respect to a center of the second photoelectric conversion portion.

3. A solid-state image sensor according to claim **1**, wherein an optical distance between the exit face of the core and the surface of the substrate is, at maximum, twice a center wavelength of light that is sensible by the first photoelectric conversion portion and the second photoelectric conversion portion.

4. A solid-state image sensor according to claim **1**, wherein, when the surface of the substrate is seen in the direction perpendicular to the substrate, a center of an entrance face of the core coincides with the center of the exit face of the core.

5. A solid-state image sensor according to claim 1, further comprising a microlens provided on the light-entrance side with respect to an entrance face of the wave guide.

6. A solid-state image sensor according to claim 5, wherein a refractive power of the microlens in a first direction in which a line connecting a center of the first photoelectric conversion portion and a center of the second photoelectric conversion portion to each other extends is lower than a refractive power of the microlens in a second direction perpendicular to the first direction in a plane parallel to the surface of the substrate.

7. A solid-state image sensor according to claim 1, further comprising a wiring line that transmits signals acquired by the first photoelectric conversion portion and the second photoelectric conversion portion, the wiring line being provided on a side of the substrate that is opposite the side on which the waveguide is provided.

8. A solid-state image sensor according to claim 1, wherein the barrier region has a potential barrier whose height is greater than or equal to a height of a potential barrier of a region excluding the barrier region and surrounding the first photoelectric conversion portion and the second photoelectric conversion portion.

9. A solid-state image sensor according to claim 1, wherein the central part is an area within a distance from a center of the pixel area of ¼ of a length of a diagonal of the pixel area.

10. A solid-state image sensor according to claim 1, wherein a direction from the center of the first photoelectric conversion portion toward the center of the second photoelectric conversion portion in a single pixel is opposite between pixels that are adjacent to each other in a direction orthogonal to the line connecting the center of the first photoelectric conversion portion and the center of the second photoelectric conversion portion to each other at the surface of the substrate.

11. A solid-state image sensor according to claim 1, wherein a signal acquired by the first photoelectric conversion portion is output if a quantity of light that is incident on the pixel is smaller than a predetermined threshold, and a signal acquired by the second photoelectric conversion portion is output if the quantity of light that is incident on the pixel is larger than the predetermined threshold.

12. A solid-state image sensor according to claim 1, wherein exposure time for the first photoelectric conversion portion is shorter than exposure time for the second photoelectric conversion portion.

13. A solid-state image sensor according to claim 12, wherein the following relationships are satisfied:

$$S1\times T1=S2\times T2, \text{ and}$$

$$C1/(S1\times T1)=C2/(S2\times T2),$$

where S1, C1, and T1 denote sensitivity, capacity, and exposure time, respectively, of the first photoelectric conversion portion, and S2, C2, and T2 denote sensitivity, capacity, and exposure time, respectively, of the second photoelectric conversion portion.

14. An image pickup apparatus comprising:

the solid-state image sensor according to claim 1 that is provided in a housing.

15. An image pickup apparatus according to claim 14, wherein an image is formed by using a signal acquired by the first photoelectric conversion portion if a quantity of light that is incident on the pixel is smaller than a predetermined threshold and by using a signal acquired by the second photoelectric conversion portion if the quantity of light that is incident on the pixel is larger than the threshold.

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